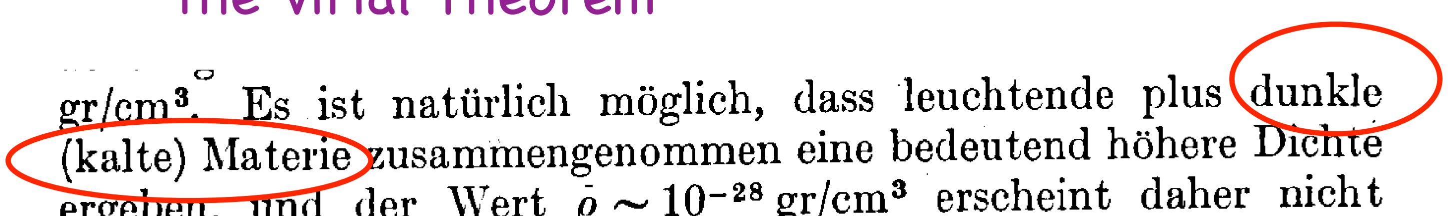
The nature of dark matter from direct and indirect searches.

Aravind Natarajan (Carnegie Mellon University)
Brookhaven National Laboratory
Cosmology seminar, March 21, 2013

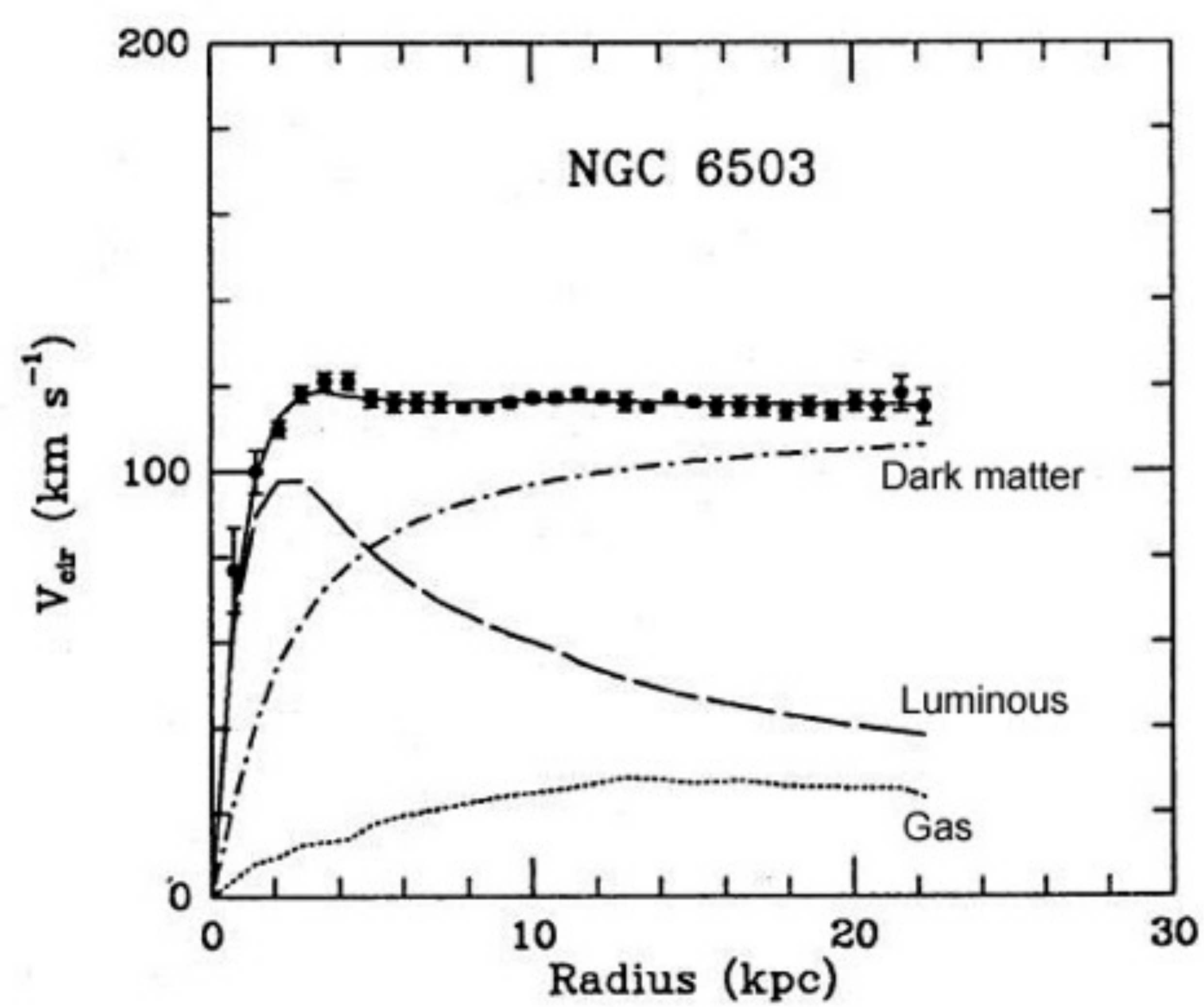
Early evidence for dark matter

The Coma cluster and
the virial Theorem



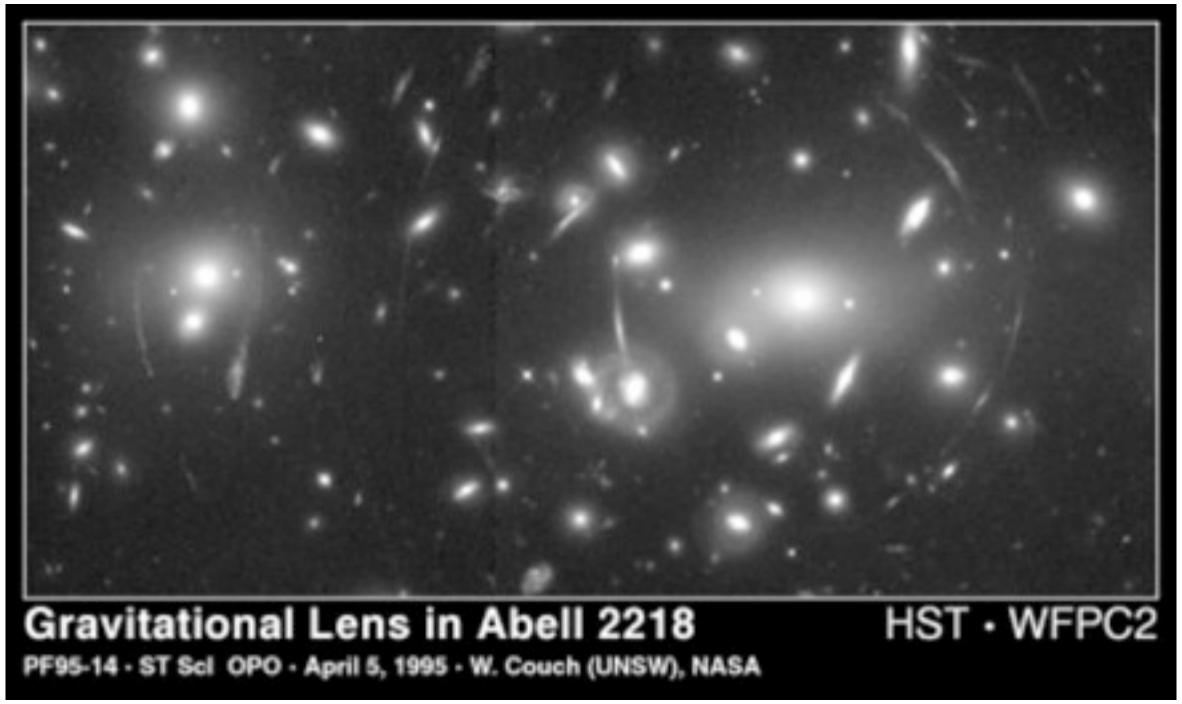
gr/cm^3. Es ist natürlich möglich, dass leuchtende plus dunkle (kalte) Materie zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\bar{\varrho} \sim 10^{-28}\ gr/cm^3$ erscheint daher nicht

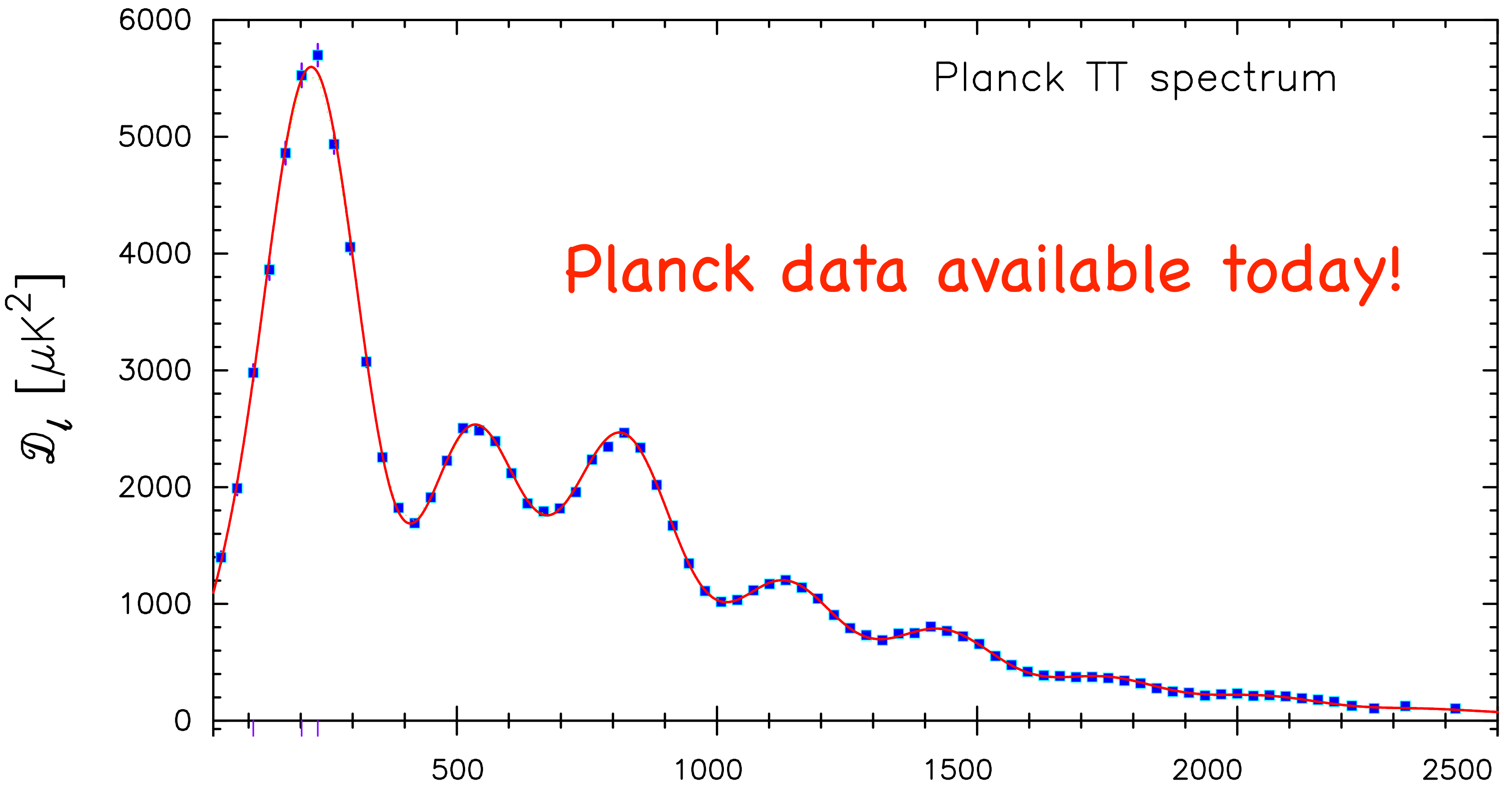
Zwicky, Helvetica Physica Acta 1933



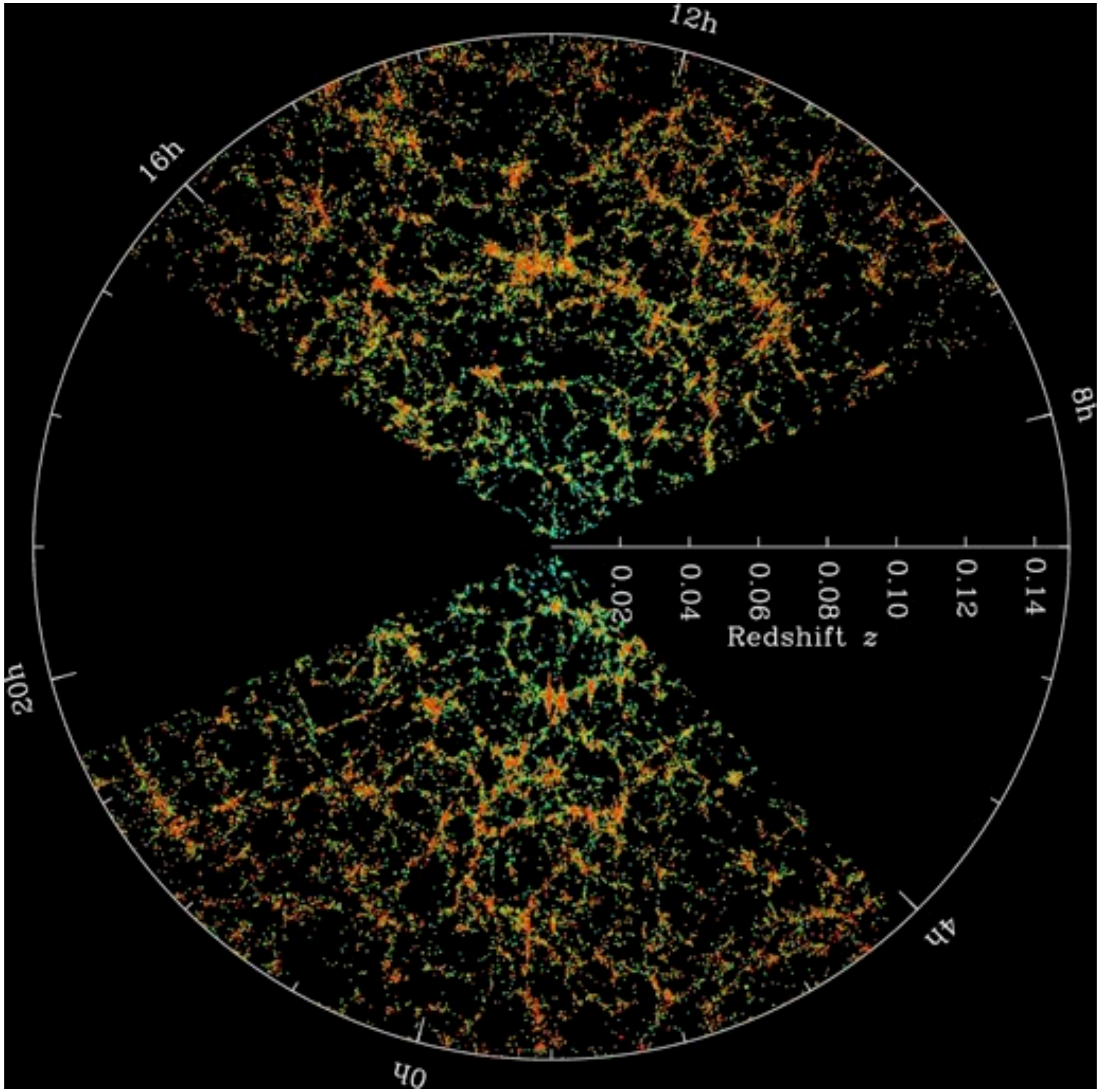
Rotation curves (Rubin & Ford 1970's)

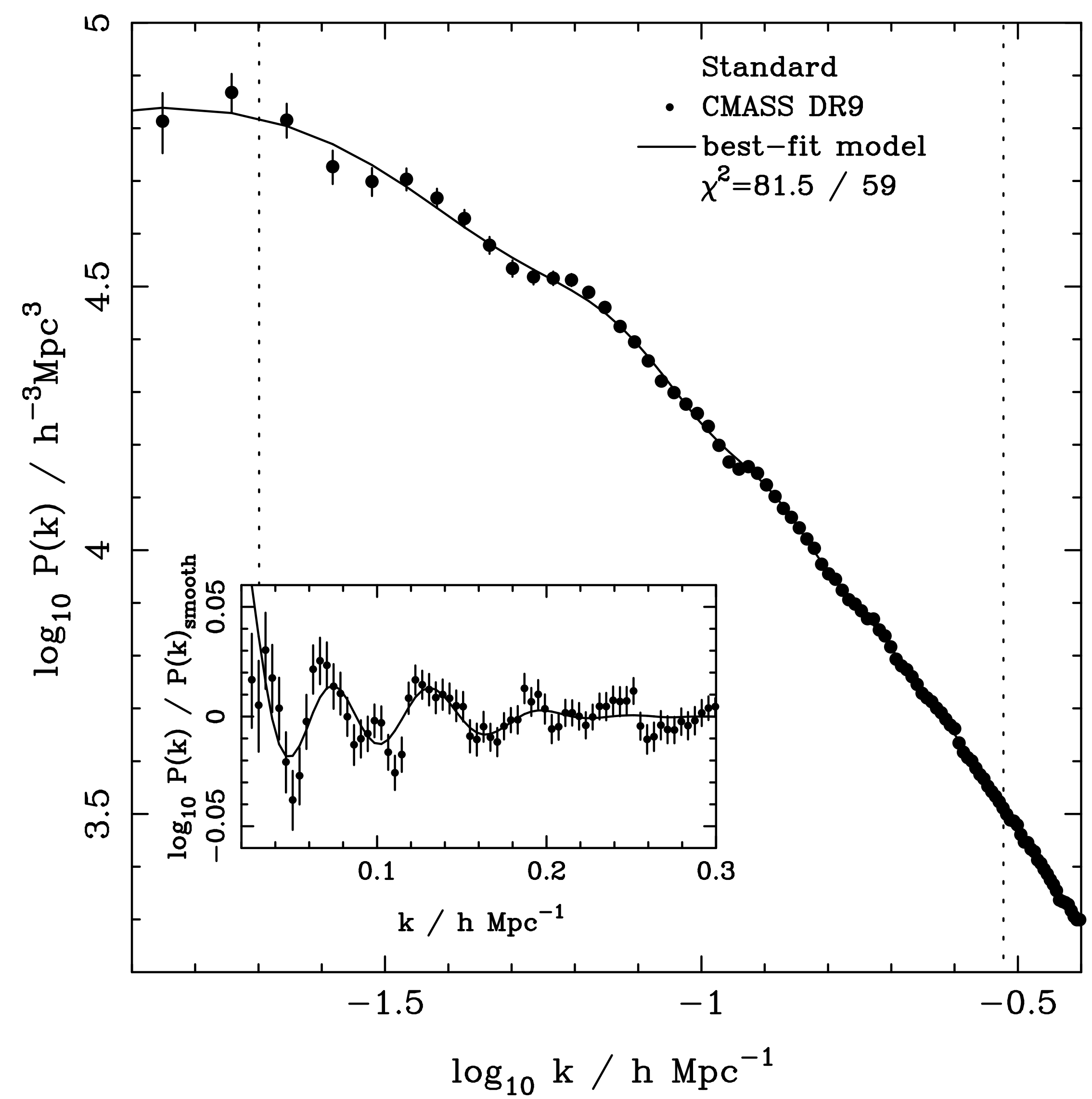
More recent observations:
Grav. Lensing and the CMB





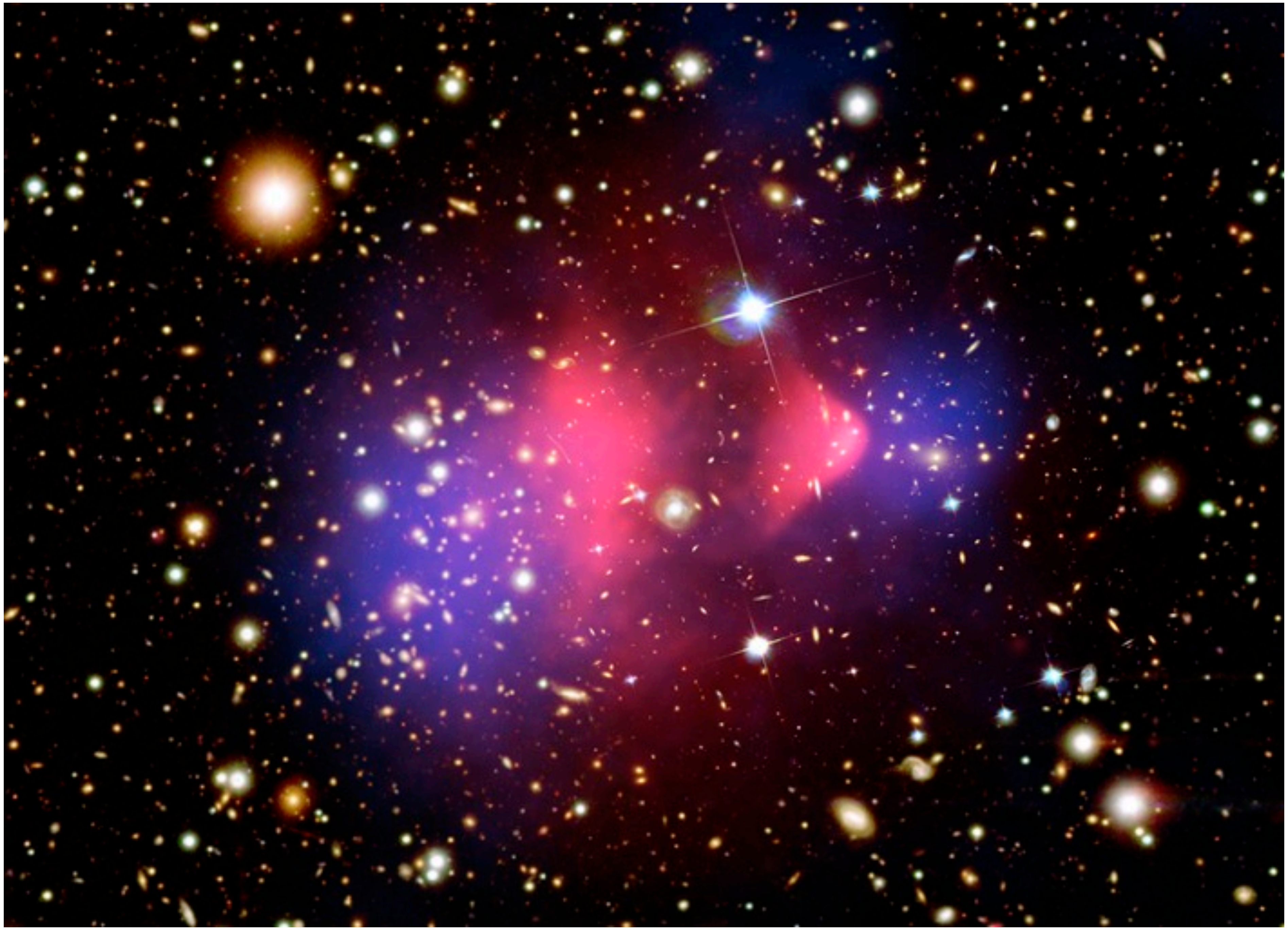
BAO and clustering of galaxies:





SDSS collaboration (2012)

The Bullet Cluster 1E 0657-558



D. Clowe, M. Brada, A.H. Gonzalez, M. Markevitch, S.W. Randall,
C. Jones and D. Zaritsky, Ap. J. 648, L109 (2006)

Outline

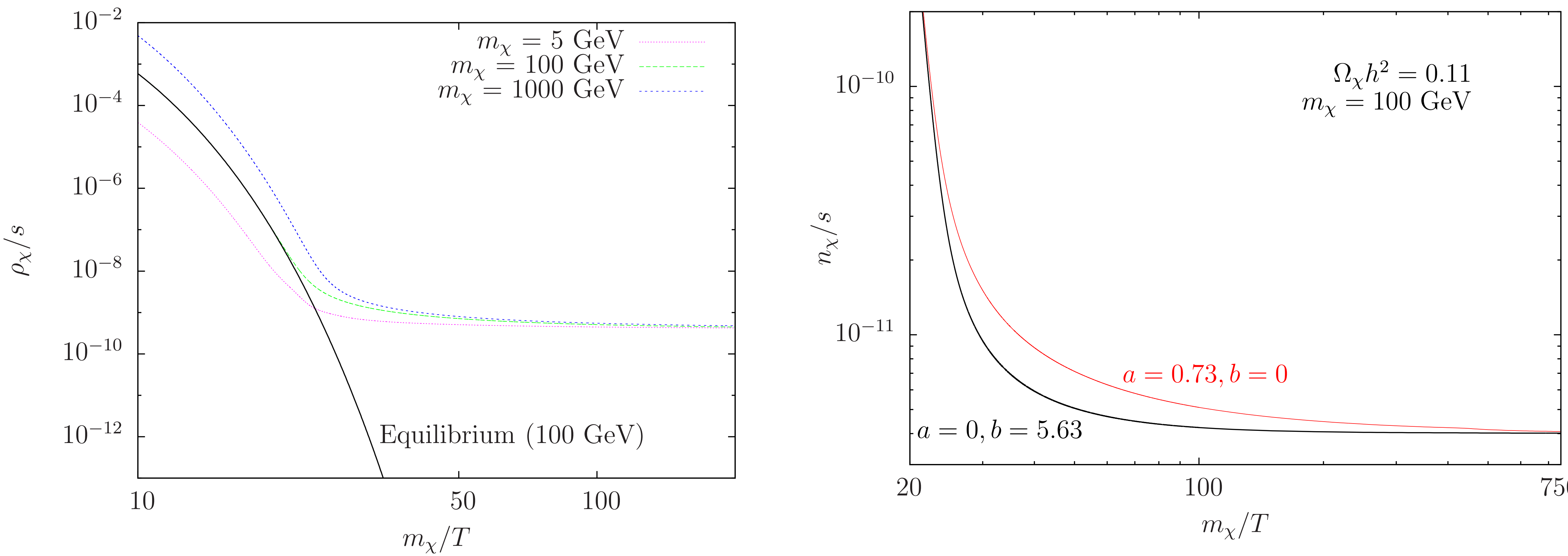
- Plenty of observational evidence for dark matter.
  But what is the dark matter composed of ??
  A good DM candidate: Weakly Interacting Massive Particles.
  Hints of WIMP dark matter from direct searches??
  DAMA/CoGeNT/CRESST Versus XENON,CDMS, ...

- WIMP indirect and collider searches:
  (i) Cosmic Microwave Background:
  What do we learn from WMAP-9 + ACT + SPT ??
  What about Planck TT (today) and EE (future) ?
  (ii) Observing dwarf galaxies at radio frequencies with the GBT.
  (iii) Collider searches: what do LHC + LEP + BELLE tell us ?

Motivation for WIMPs

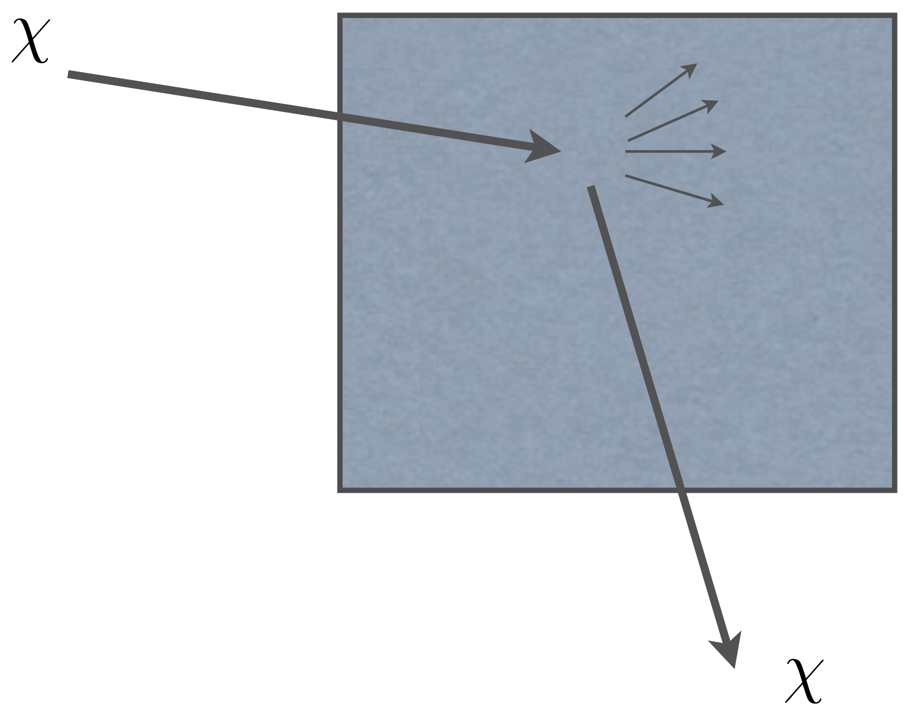
- Were suggested to solve problems in particle physics unrelated to dark matter.

- Have weak interactions in addition to gravity.

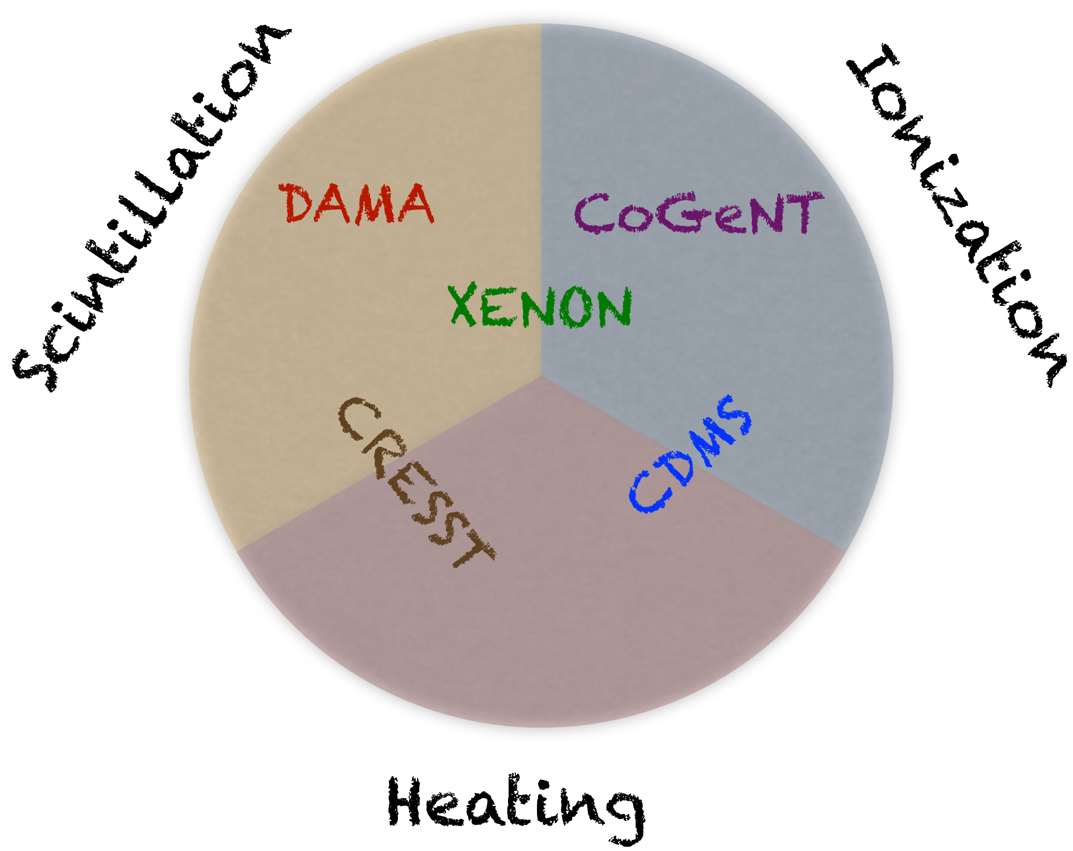


$$\Omega_\chi h^2 \approx 0.11 \;\Rightarrow\; \langle \sigma_{\rm a} v \rangle \approx 2.18 \times 10^{-26}\ {\rm cm}^3/{\rm s}$$

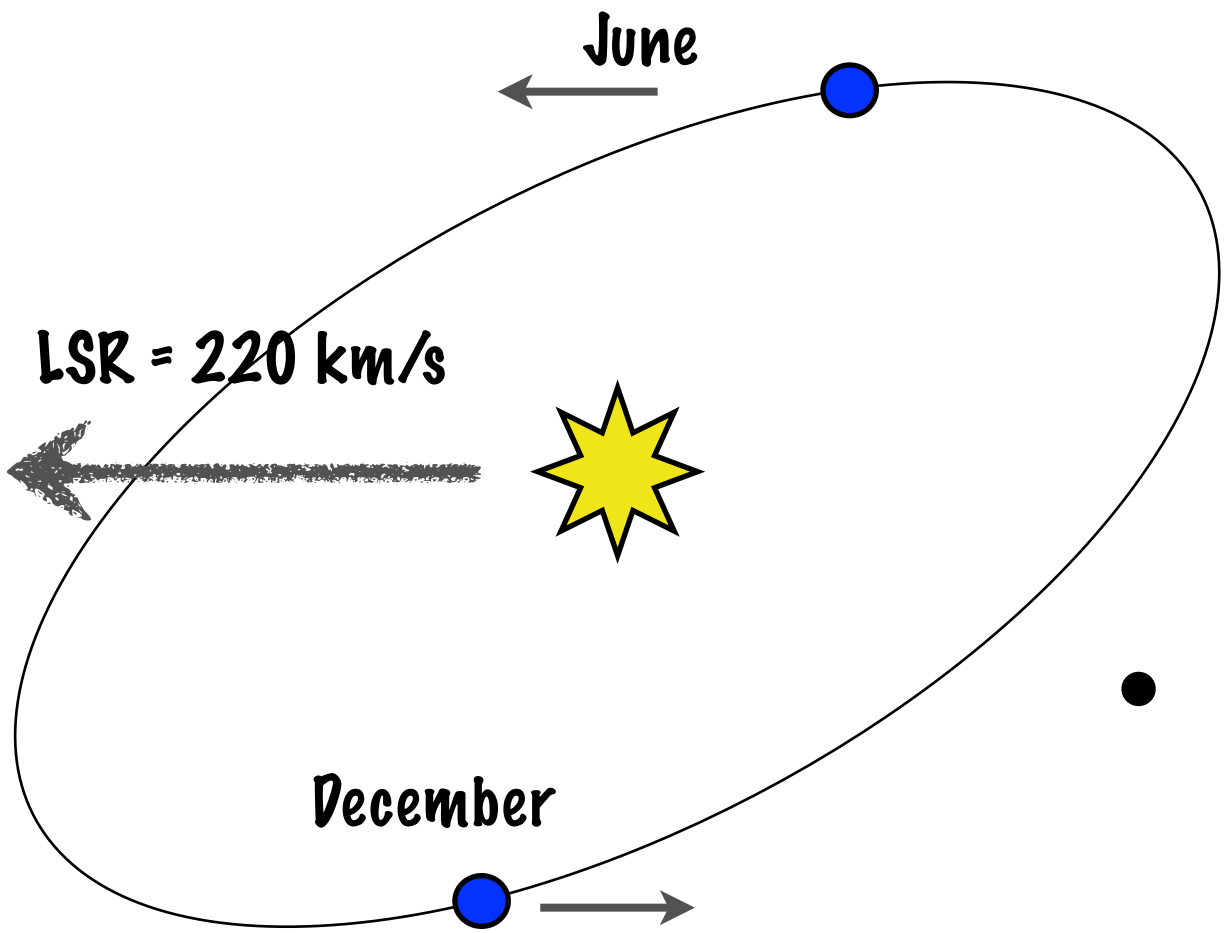
WIMP - nucleon scattering



Goodman & Witten 1985
Griest 1988
Engel 1991

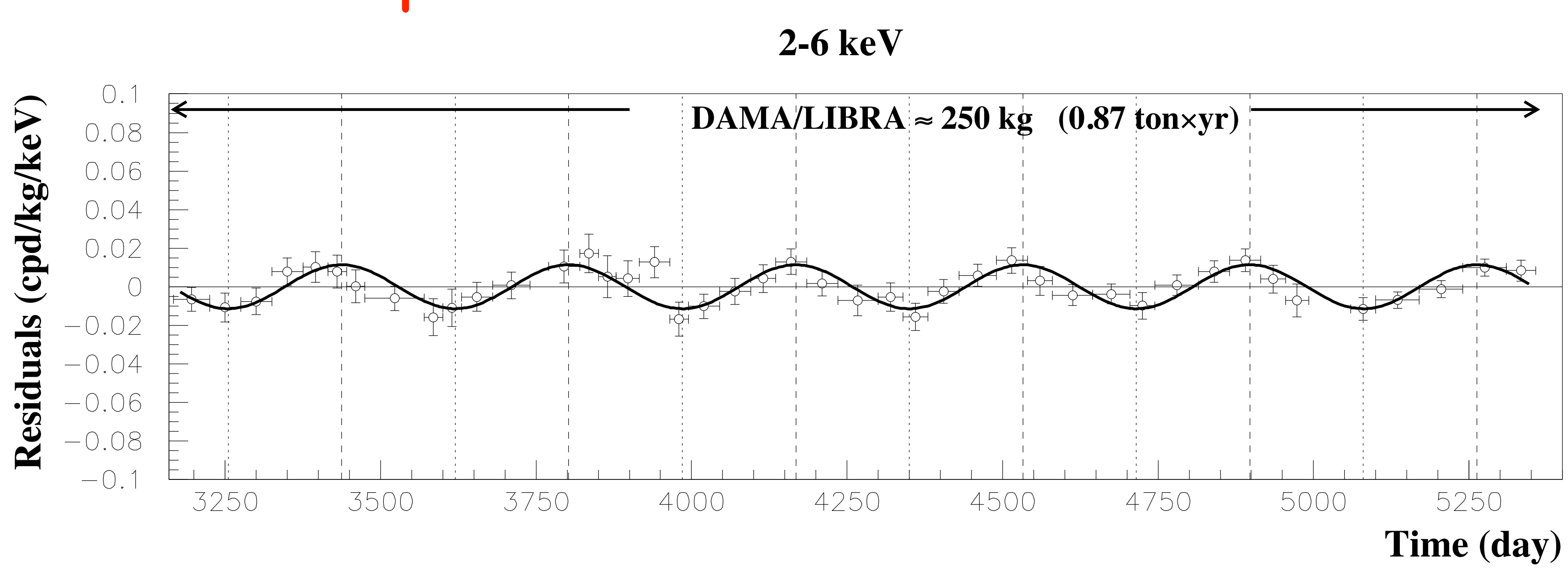


DAMA and Annual Modulation



- Taking data since 2003 in the Gran Sasso mine
- Looks for scintillation light using PMTs.
- With earlier DAMA/NaI, exposure is 1.17 ton-year (13 annual cycles).

Single hit events show a modulation at 8.9 σ
Multiple hit events consistent with zero modulation.

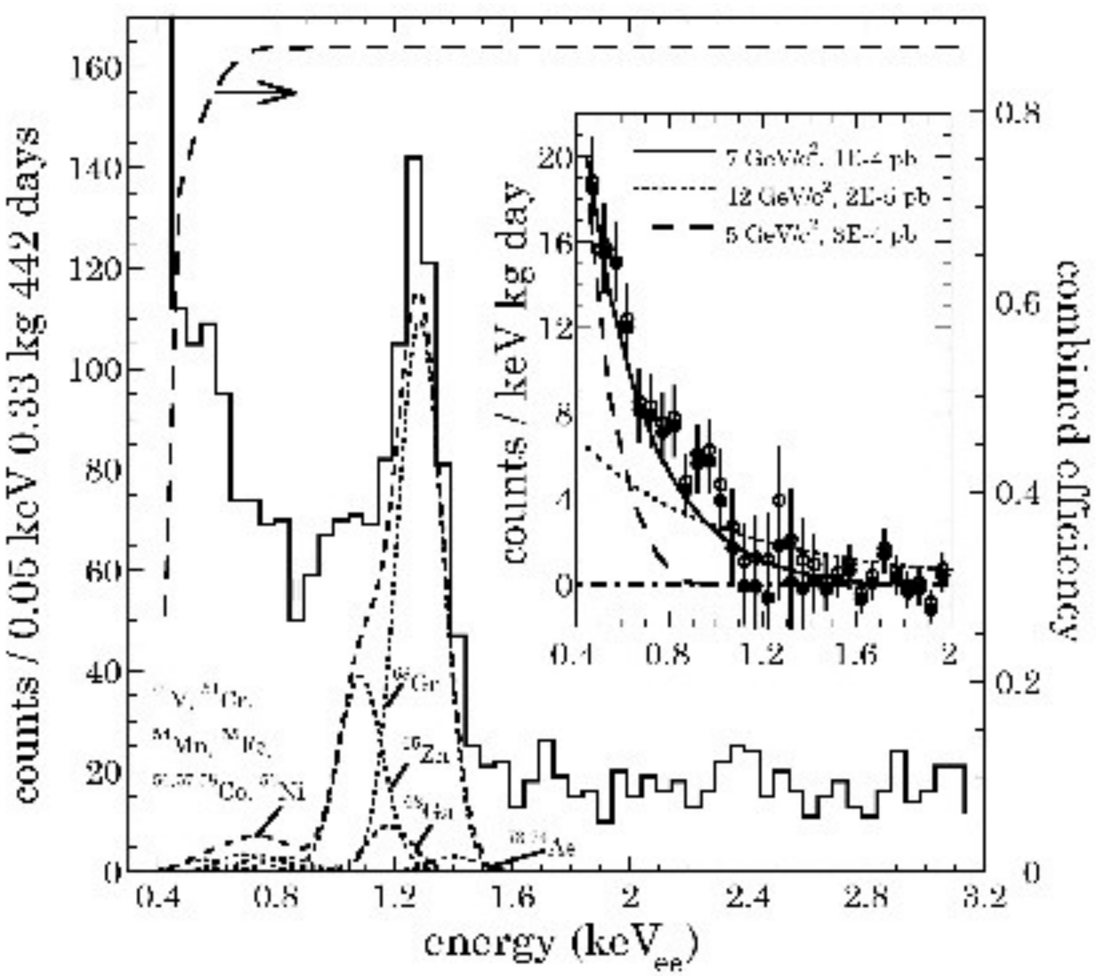


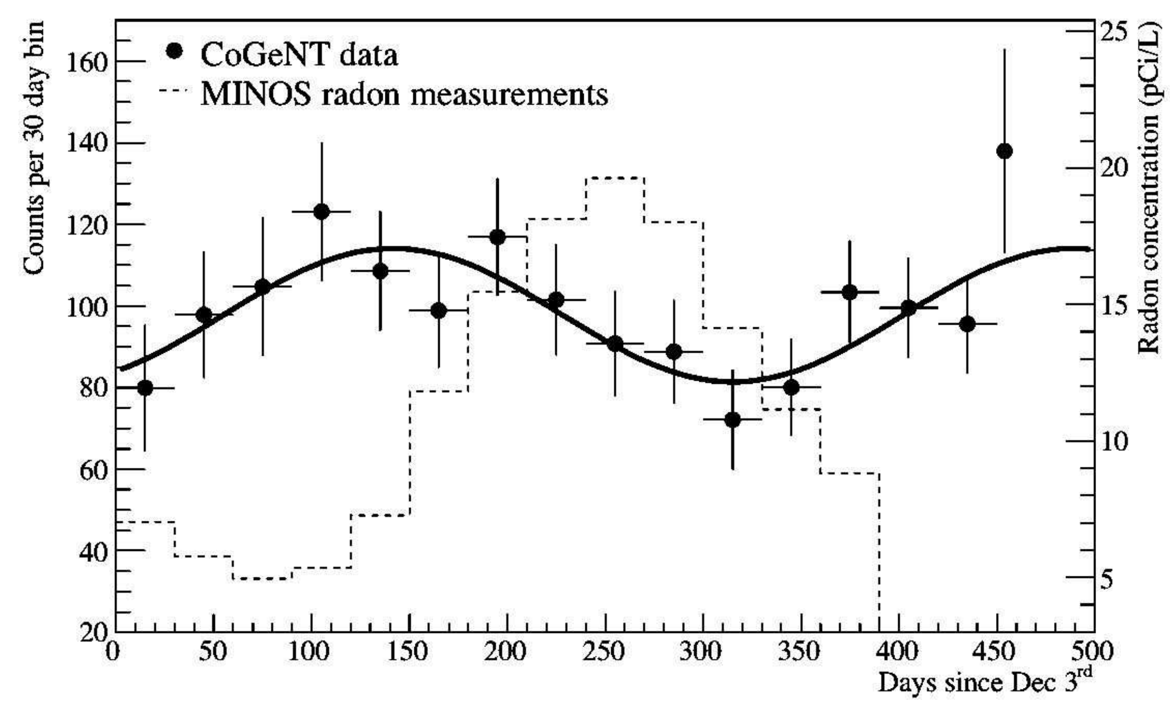
R. Bernabei et al. for DAMA, 2010

CoGeNT

- Low threshold Germanium detector.
- Results in 2010 with 56 days of data
  - excess events at low energies.

- New results in 2011 confirm excess events at low energies.
  15 months of data. Annual modulation at 2.8 σ



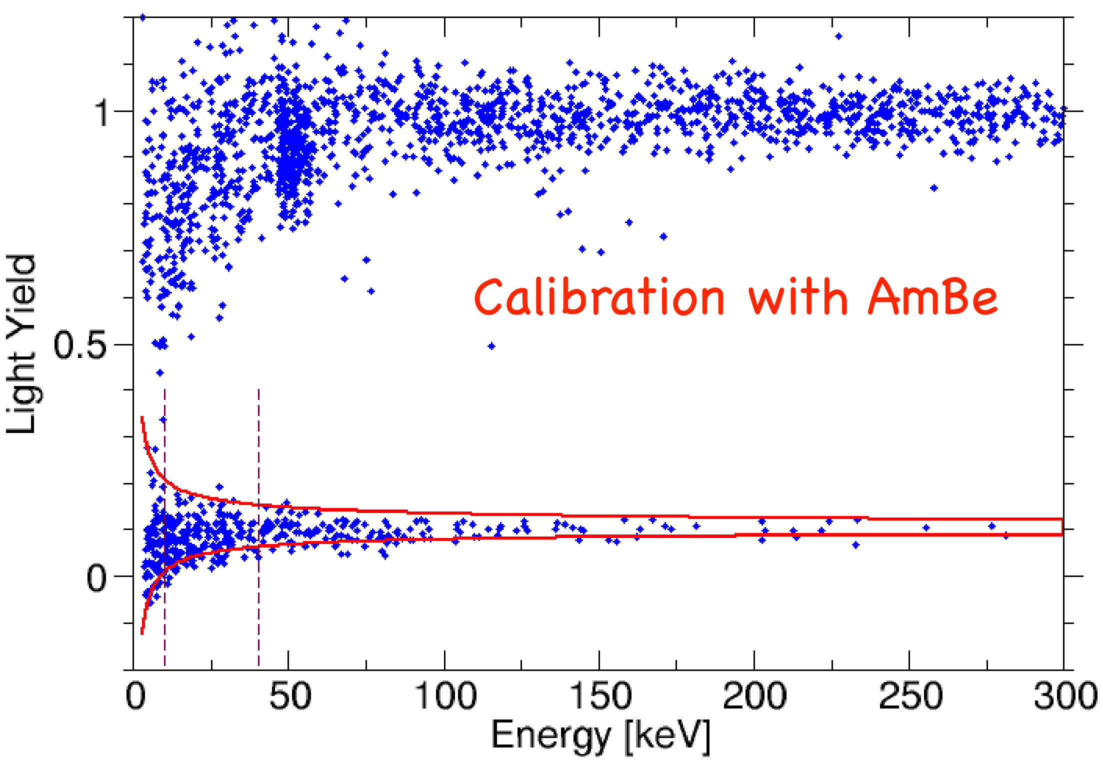


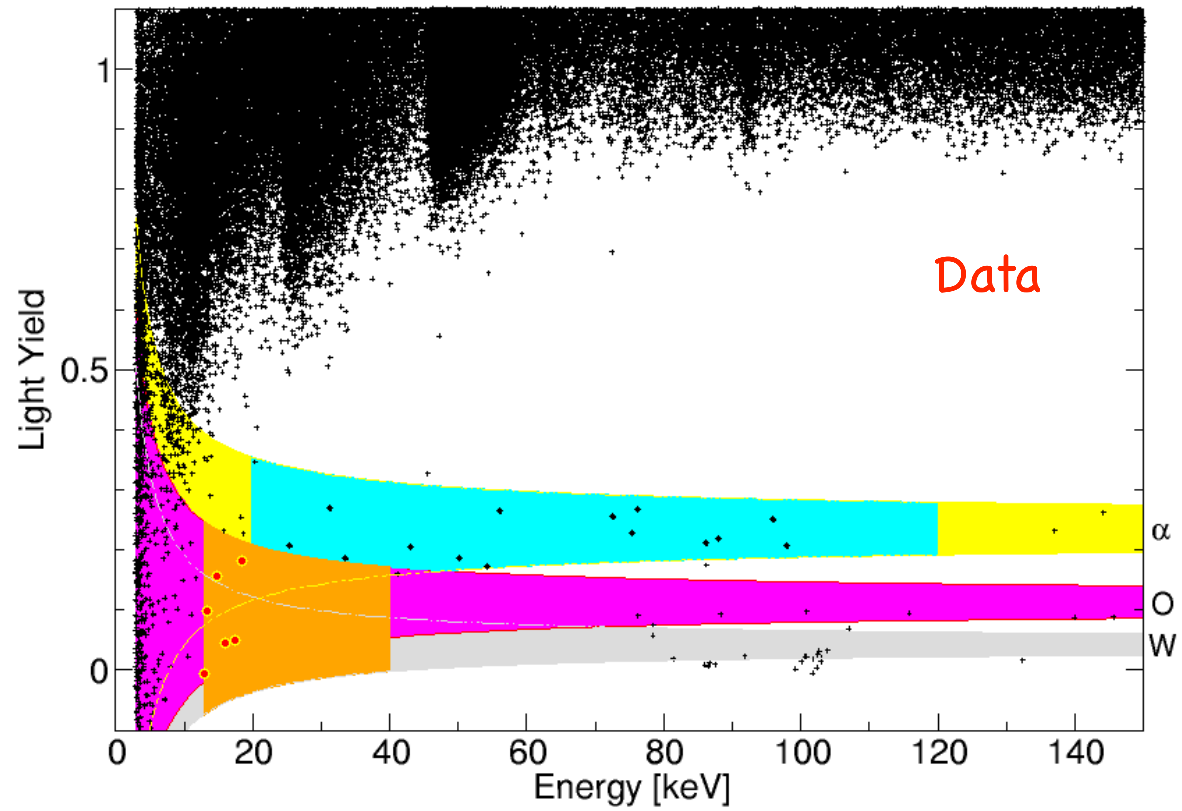
Aalseth et al. for CoGeNT 2011, 2012

CRESST

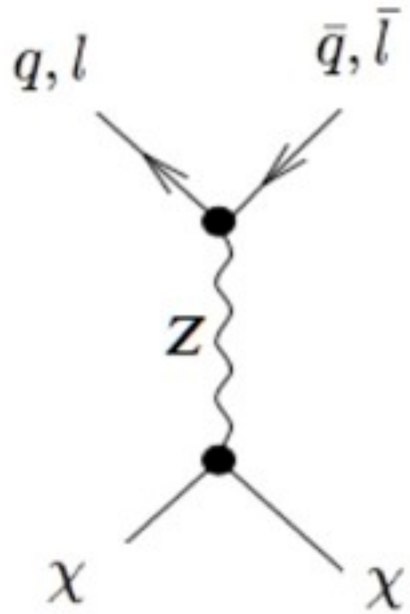
Angloher et al 2011

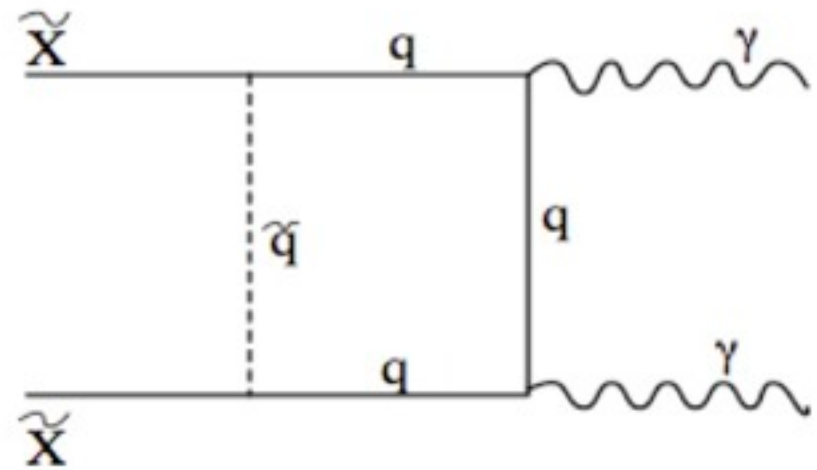
- Target = $CaWO_4$ Gran Sasso mine.
- Transition Edge Sensors (TES) made of Tungsten.
  Scintillation light together with Phonon signal.
- Can distinguish electron/photons from WIMPs/neutrons.
- Results in 2011 with 730 kg.days
  Excess events consistent with light WIMPs.





Low mass DM can be tested with the CMB





- CMB is well understood (linear physics)
  and very well measured by WMAP + Planck + ACT/SPT.

- DM annihilation is most important at high redshifts z > 100
  Thus halos are not very important.
  No astrophysical backgrounds to worry about.

DM annihilation to standard model particles

$$\chi\chi \longrightarrow b\bar{b}$$

$$\searrow\; e^{\pm},\ p\bar{p},\ d\bar{d},\ \gamma\gamma,\ \nu\bar{\nu}$$

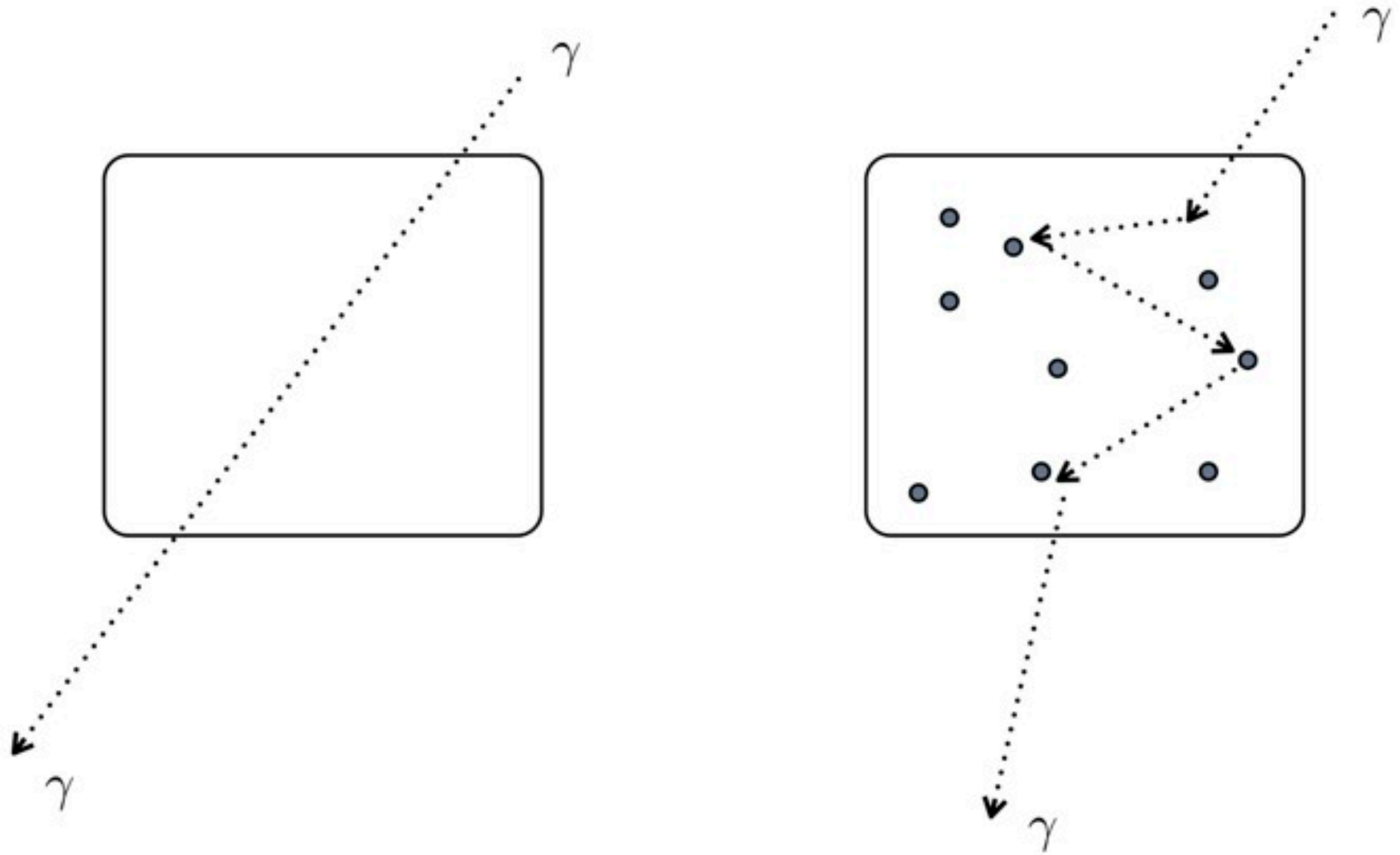
- $e^{\pm}$: inverse Compton scatter with the CMB very quickly
  --> Boost CMB to higher energies.
  Medium energy photons photoionize the gas.

- $p^{\pm}$ inverse Compton scatter slowly.

- γ Delbruck scatter with the CMB.
  Ionize and Compton scatter with neutral atoms.

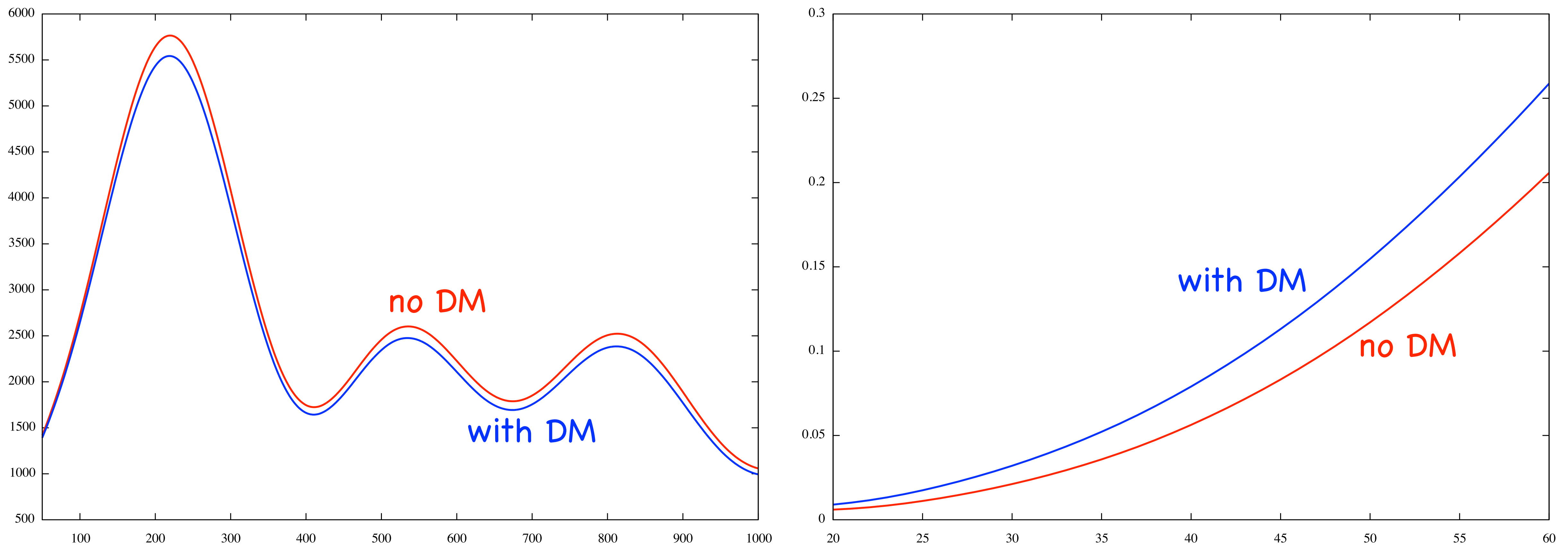
A.N. & Schwarz 2009, 2010; Cirelli & Panci 2009; Belikov & Hooper 2009;
Slatyer, Padmanabhan, & Finkbeiner 2009; Furlanetto & Stoever 2010

DM annihilation to standard model particles



$$\tau = \int dt\, c\, n_{\mathrm{e}}(z)\, \sigma_{\mathrm{T}}$$

TT damped on small scales
EE boosted on large scales

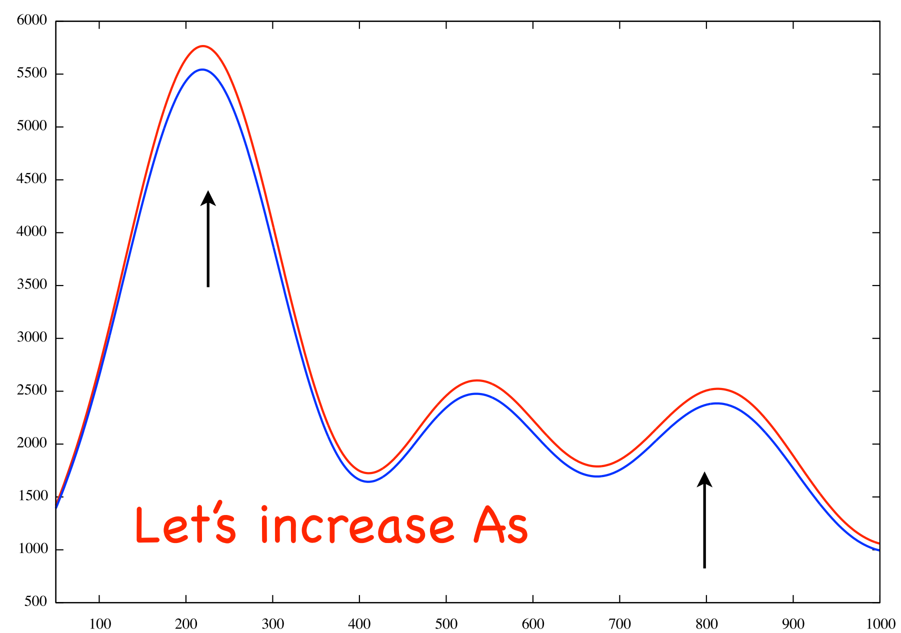


A.N. 2012, A.N. et al. in preparation.

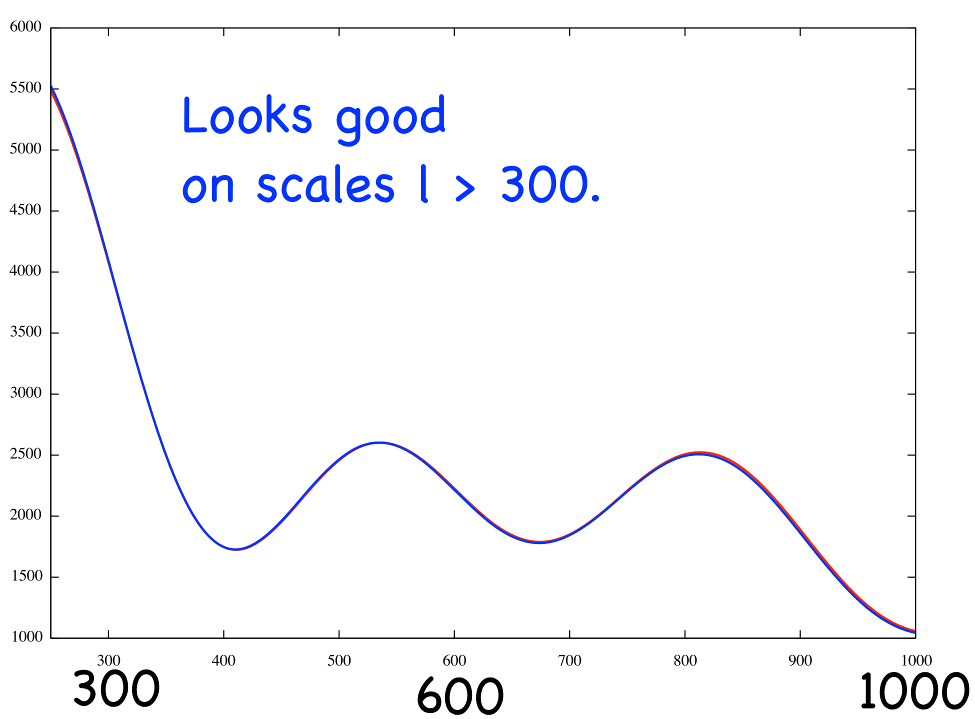
Damping of the TT spectrum is scale dependent due to causality

$$C_l \propto A_\mathrm{s}\,(k/k_\mathrm{pivot})^{n_\mathrm{s}}\,e^{-\tau}$$

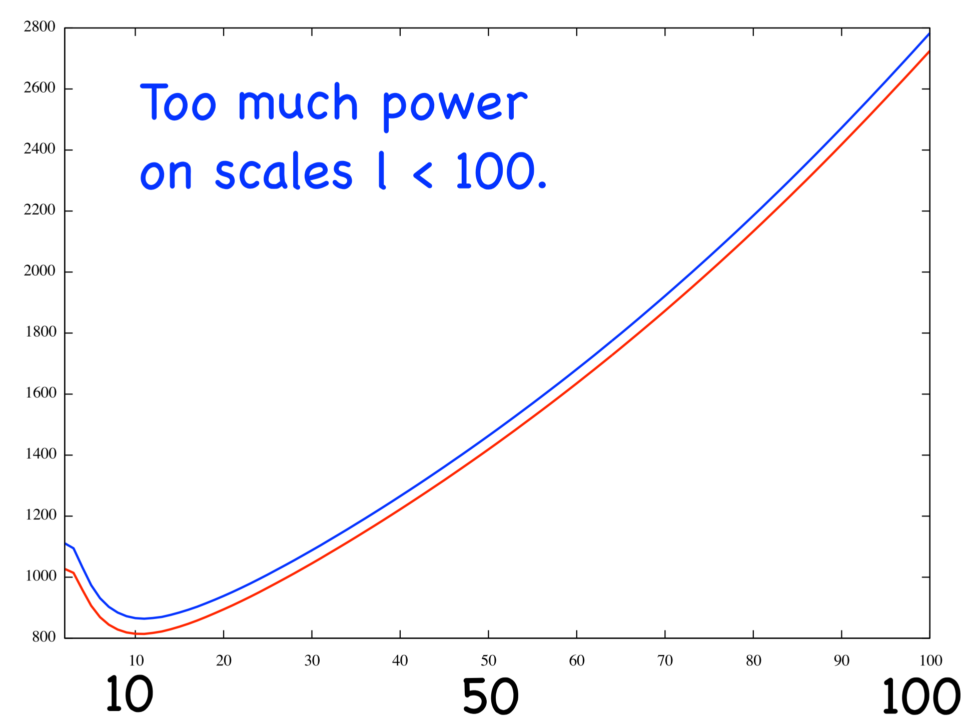
Let's keep n_s fixed, but increase As



Red: no DM
Blue: with DM



BUT



Damping of the TT spectrum is scale dependent due to causality

$$C_l \propto A_s \left(k/k_{\mathrm{pivot}}\right)^{n_s} e^{-\tau}$$

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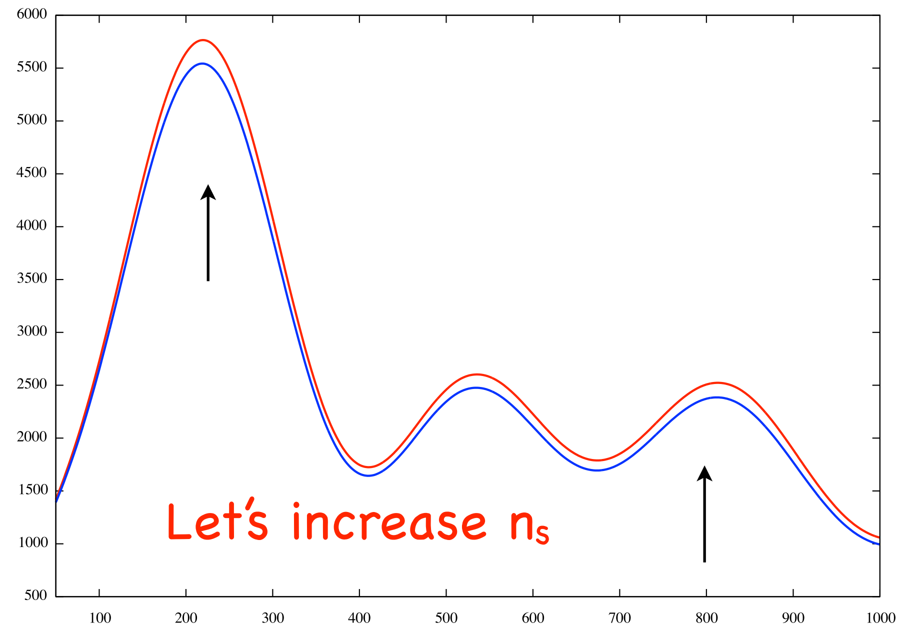

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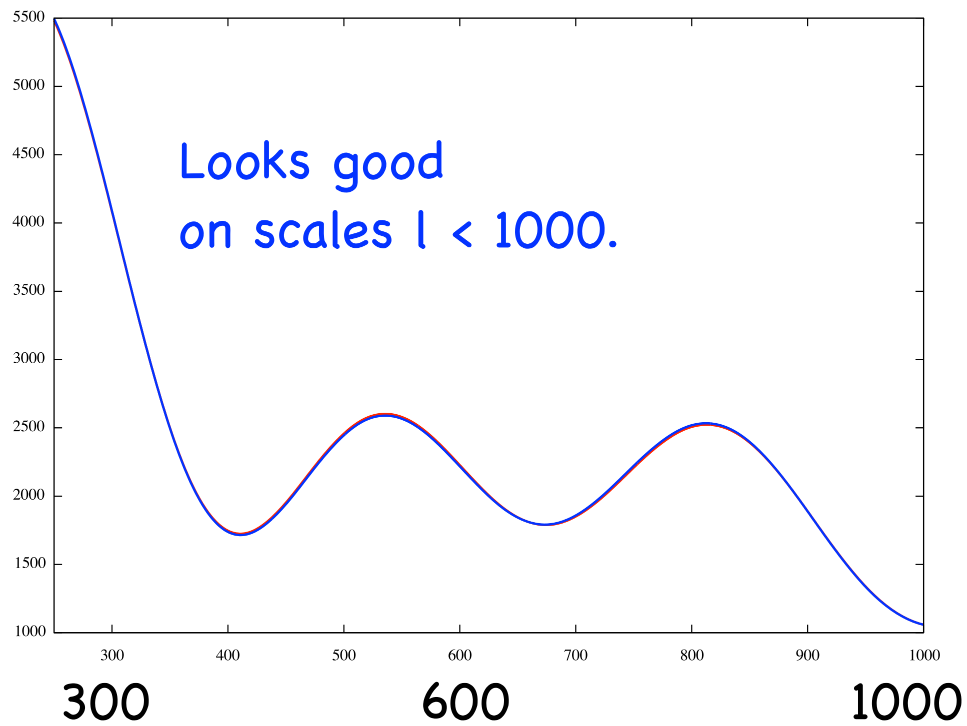

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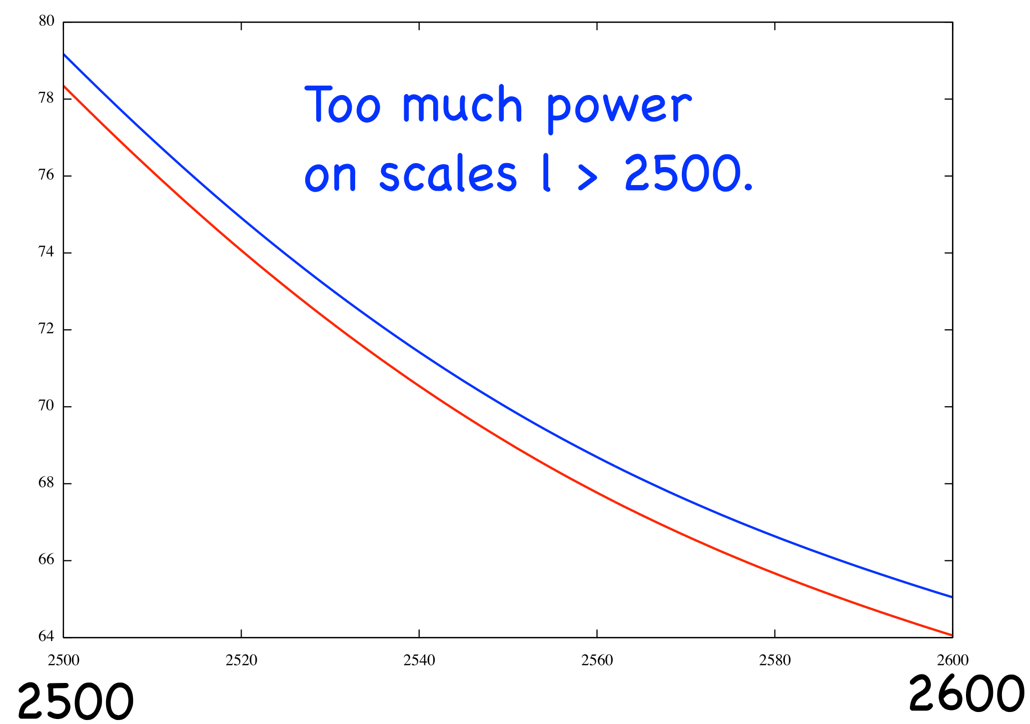


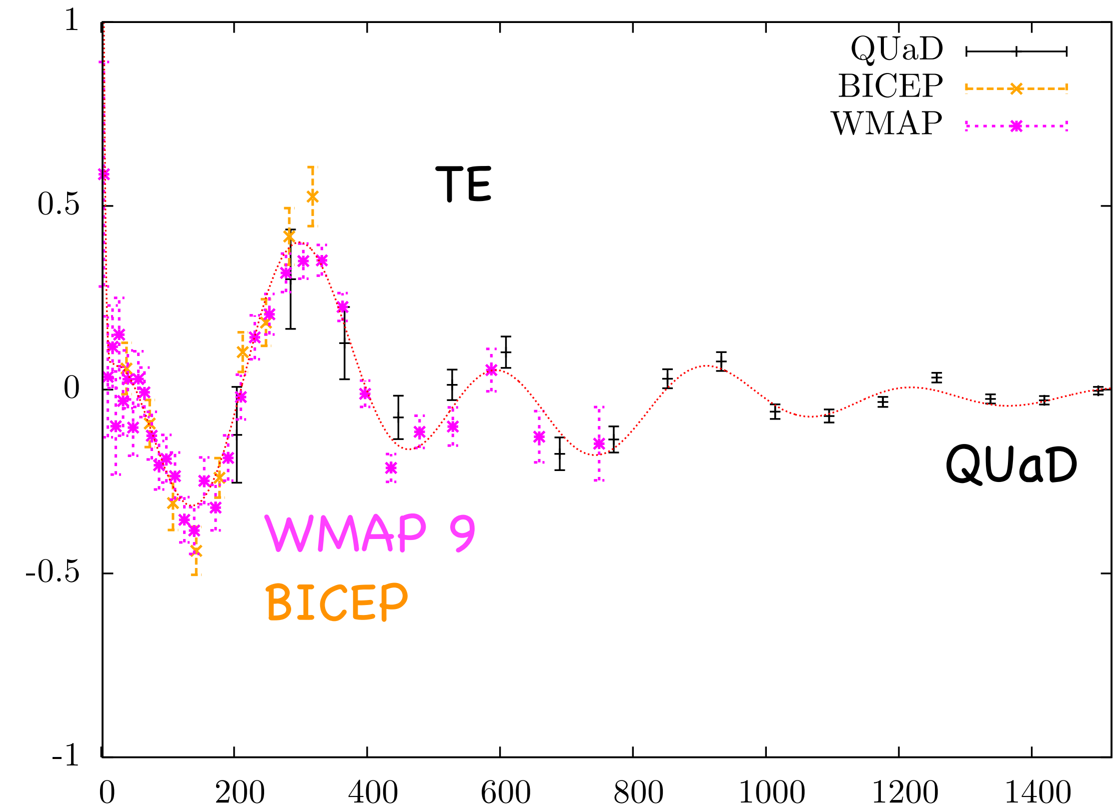
CMB Data & Variables

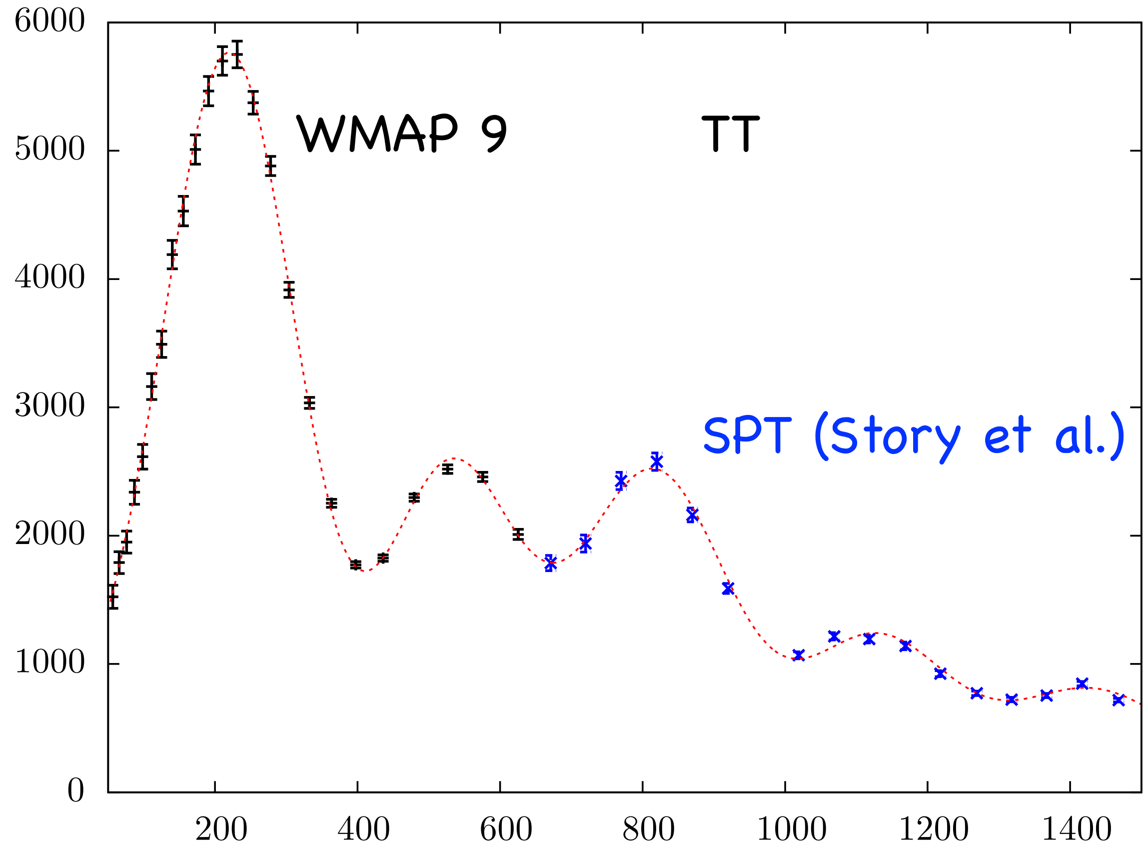
$$\tau, n_\mathrm{s}, A_\mathrm{s}, h, \Omega_\mathrm{c}h^2, \Omega_\mathrm{b}h^2, m_\chi$$

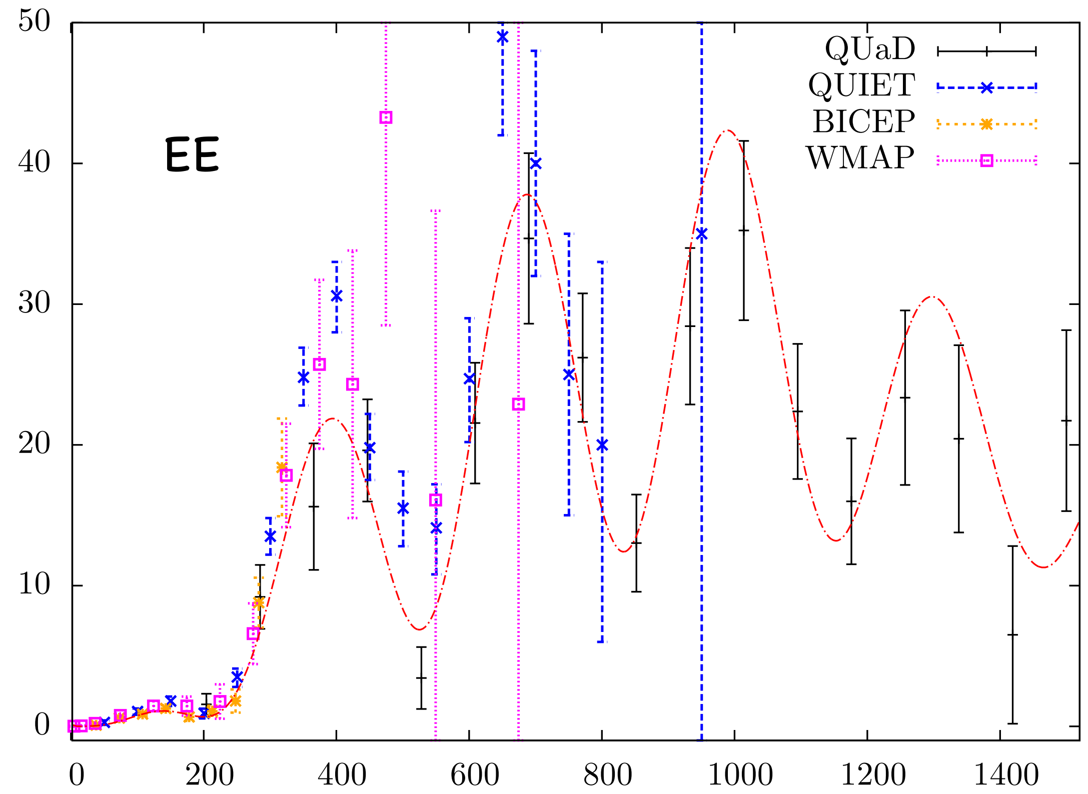
+ SZ, IR (Poisson), IR (clust.)

MontePython & CLASS

Audren et al. 2013; Lesgourgues et al. 2012

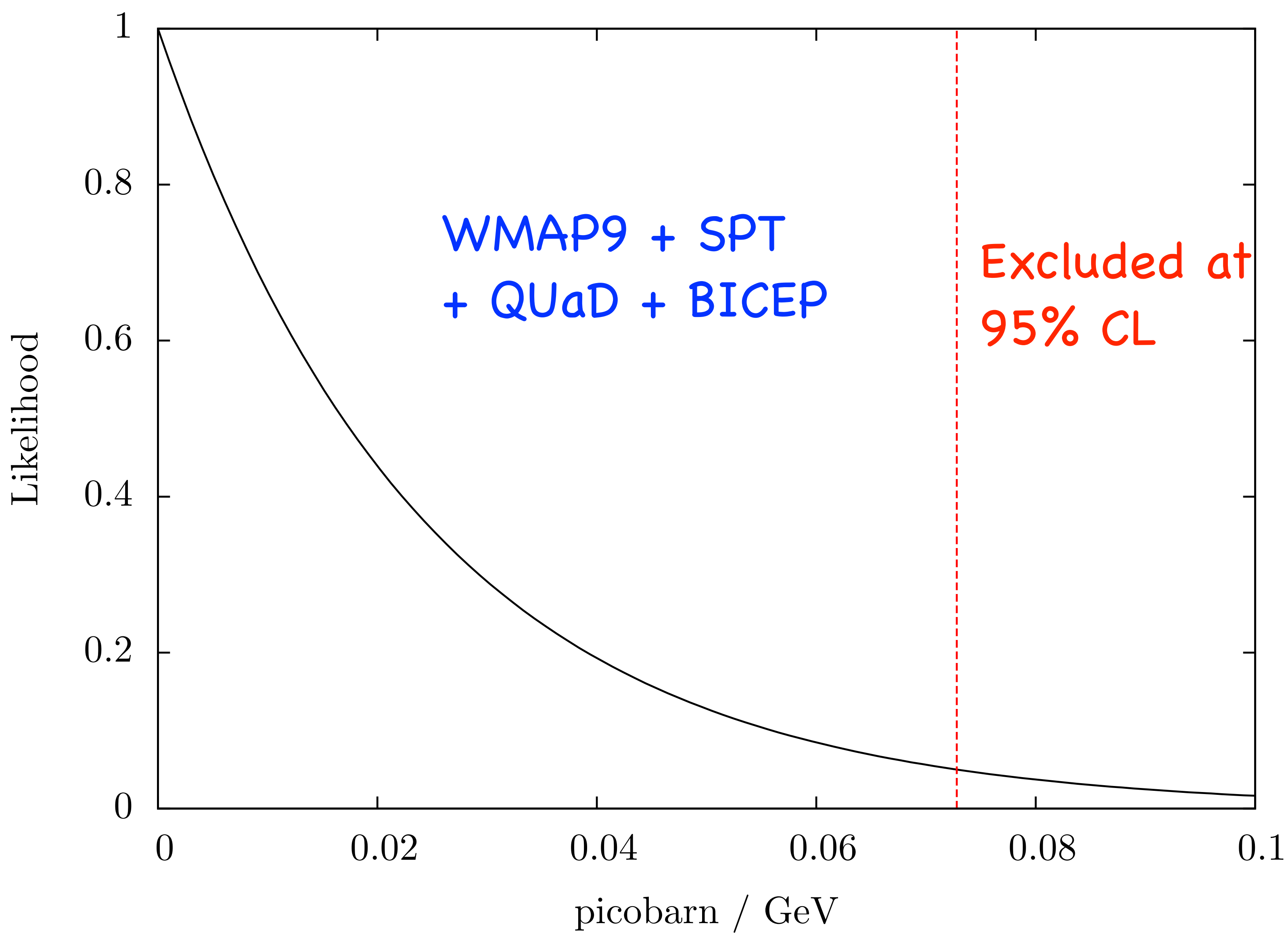






The likelihood function:

marginalized over $\tau, n_{\rm s}, A_{\rm s}, h, \Omega_{\rm c}h^2, \Omega_{\rm b}h^2$
and over SZ, IR(p), IR(cl)



$$\xi = \frac{\langle \sigma_{\rm a} v \rangle}{m_\chi} f_{\rm em} \bar{f}_{\rm abs}(z)$$

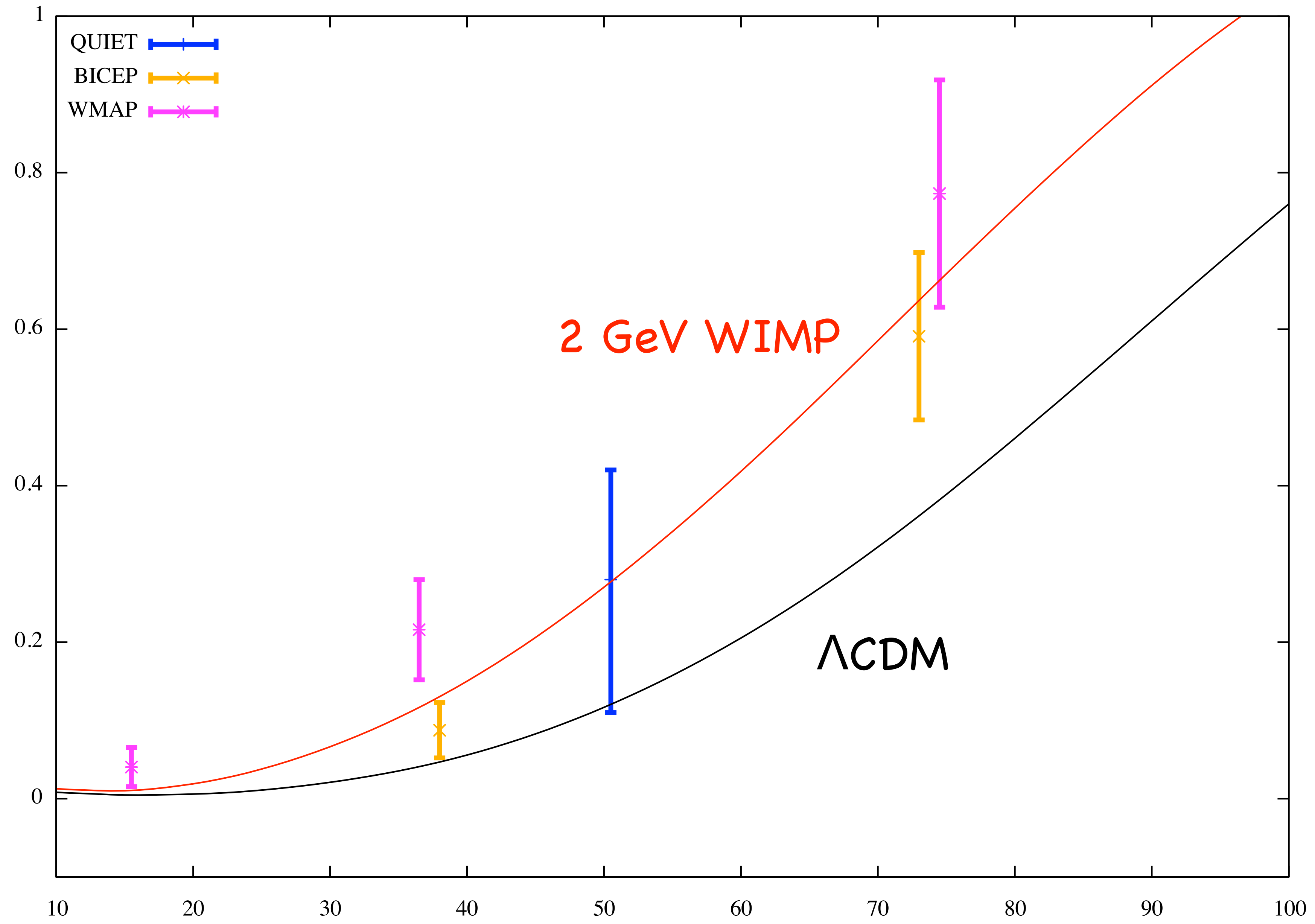
< 0.073 pb.c/GeV

==> m > 13 GeV e^+e^-

Planck (today)
< 0.184 pb.c/GeV

A.N. 2012; A.N. et al. in preparation.

What about the low l polarization ?



weak support for DM ?

What to expect from Planck TT

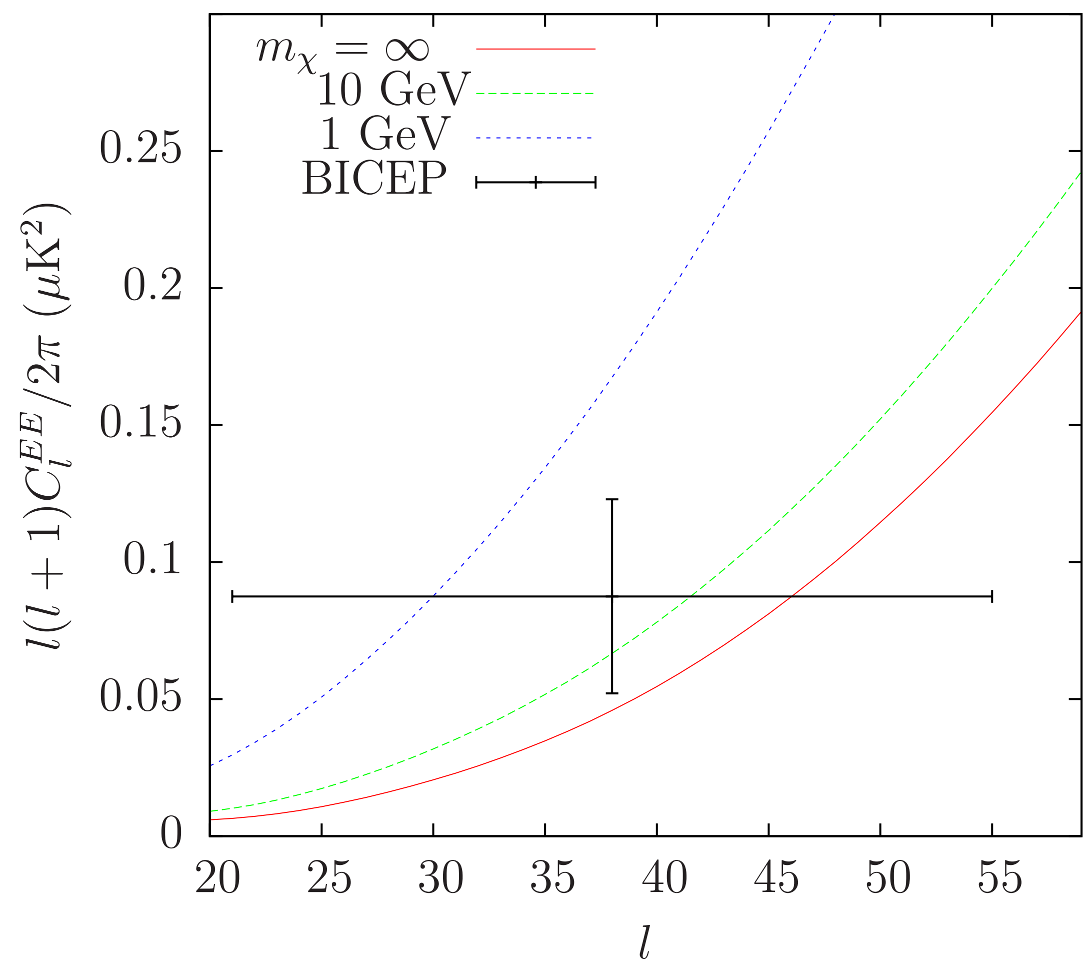
Error bars:

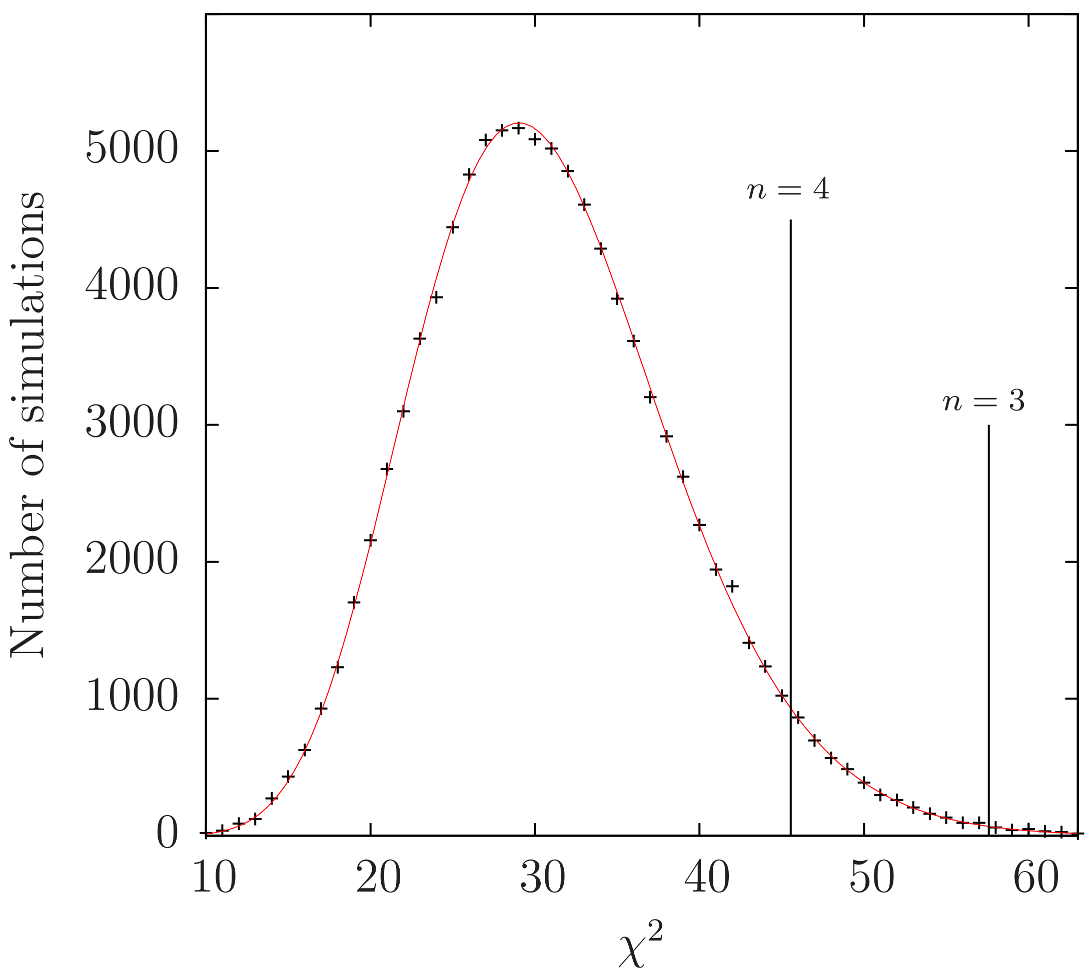
$$\frac{\delta C_l^{EE}}{C_l^{EE}} = \sqrt{\frac{2}{2l+1}}\frac{1}{f_{\rm sky}^{1/2}}\left[1 + \frac{(f_{\rm sky} w)^{-1}}{C_l^{EE}} e^{l(l+1)\sigma_{\rm b}^2}\right]$$

FWHM = 7′ for the 143 GHz channel
==> cosmic variance limited until l = 1200

Big improvement over WMAP from l = 600 to l ≈ 2000
For l > 2000, ACT/SPT wins due to smaller beam.

What to expect from Planck EE





Expected Planck EE error bars in the low l EE
= few x cosmic variance !

By contrast WMAP EE error bar at l = 40
= 47 x cosmic variance :(

Other forms of indirect detection:

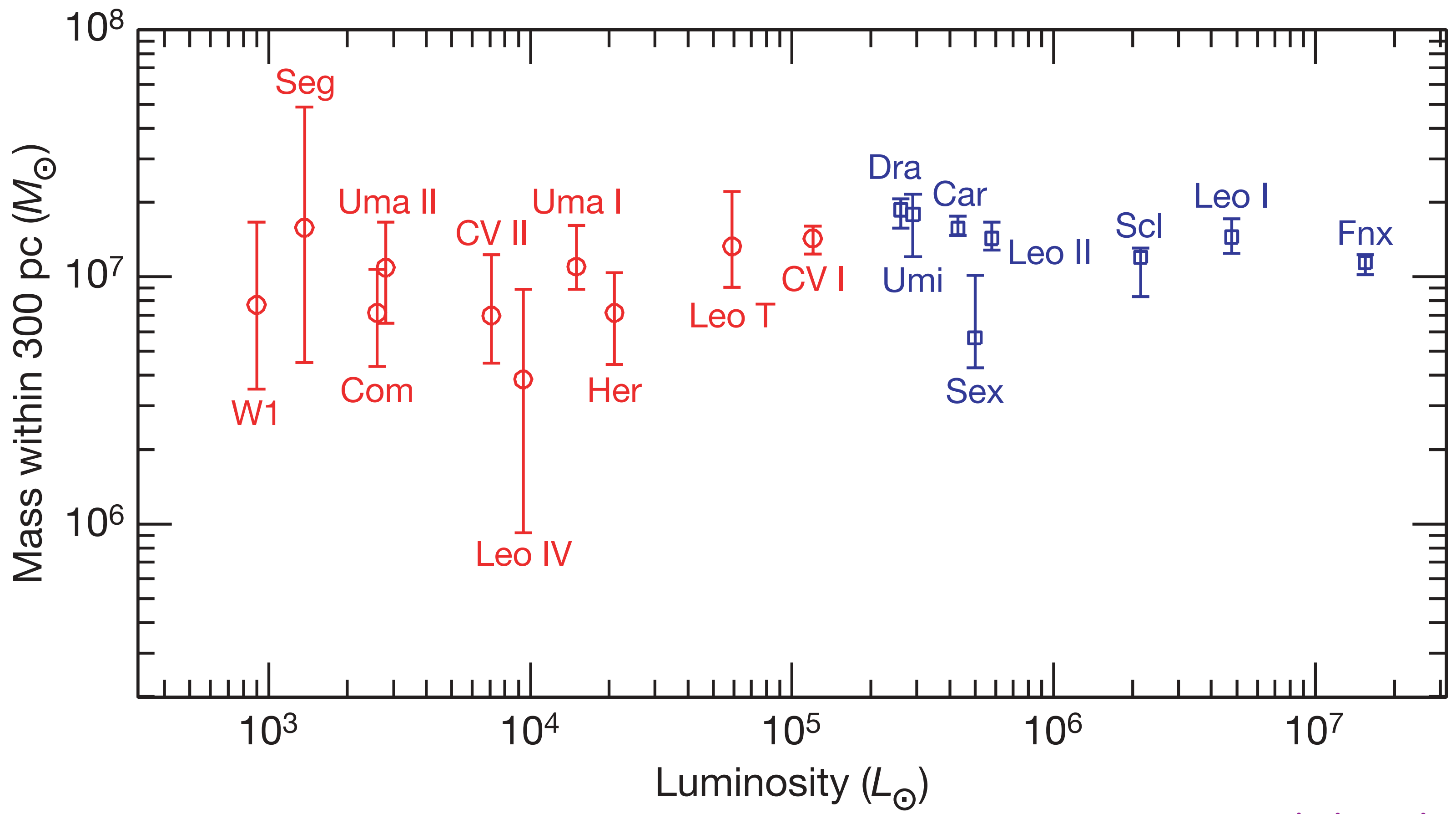
The CMB is great to test low mass WIMPs.
Let's look at other forms of indirect detection.

Gamma rays from DM annihilation ?
(works, good only for low mass DM)

is there a technique good for large DM masses ?
Yes - Radio observations !
Synchrotron from DM annihilation in dwarfs.

Radio observations of dwarf galaxies

- Dark matter dominated. Low astrophysical background.
- Dark Matter annihilation in dwarf galaxies produces e^+/e^- in addition to photons and neutrinos.
- Relativistic charged particles moving in a magnetic field emit synchrotron radiation.

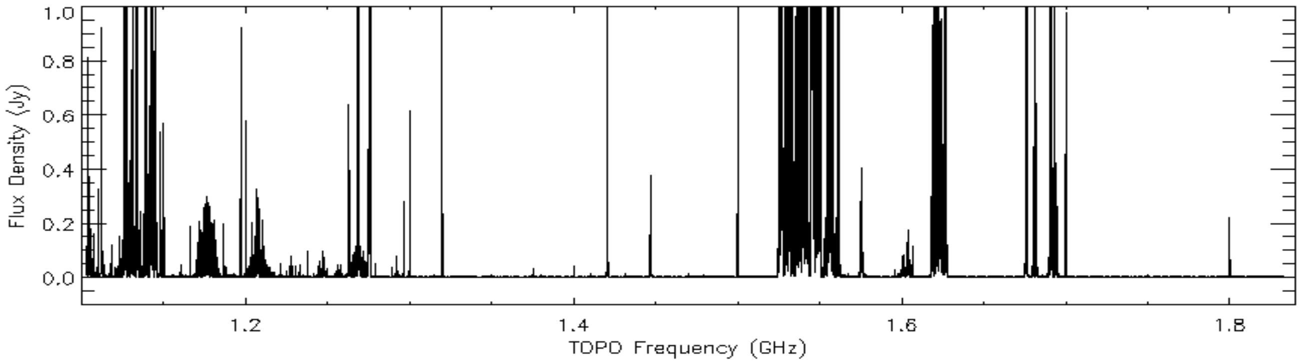


Strigari et al. 2008

Observations with the Green Bank Telescope at 1.4 GHz

A.N., Peterson, Voytek, Spekkens, Aguirre, Mason, in preparation.

RFI plot

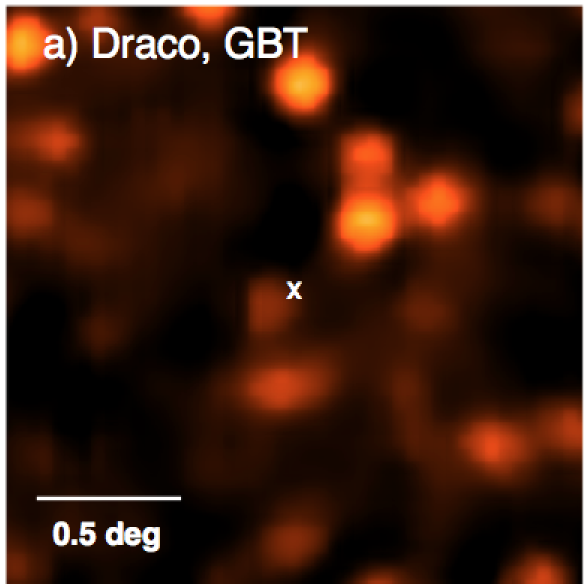


NVSS catalog
--> VLA at 1.4 GHz
all point sources north of -40 dec.

- Large synchrotron flux from DM annihilation.
- Absence of strong RFI sources.
- Ability to subtract point sources using an external catalog.

Deep radio observations of nearby dSphs.

K. Spekkens et al. arXiv: 1301.5306



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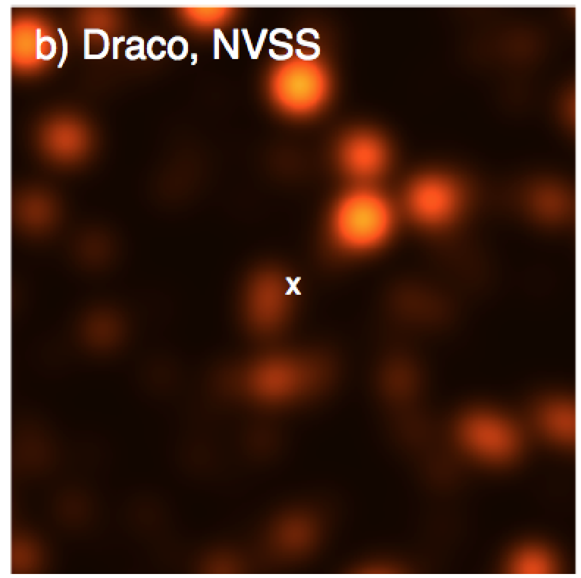

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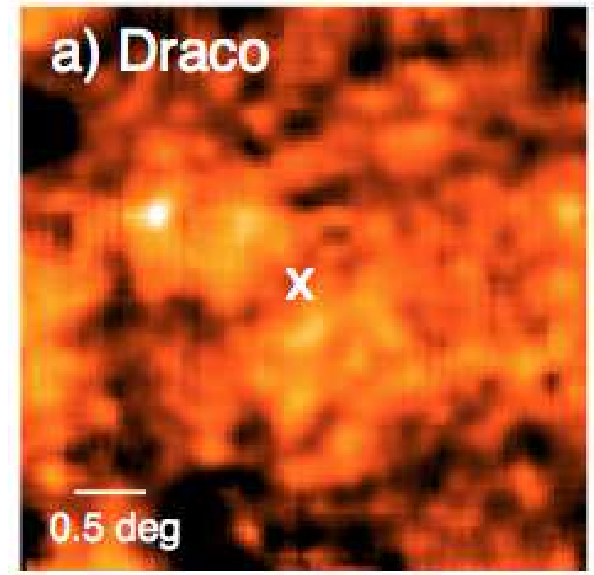
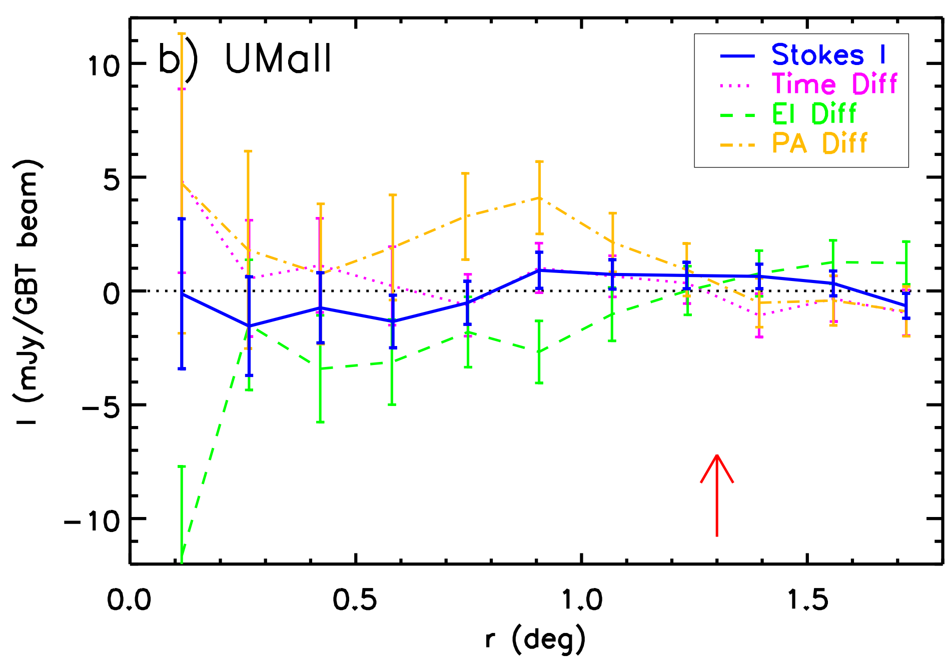
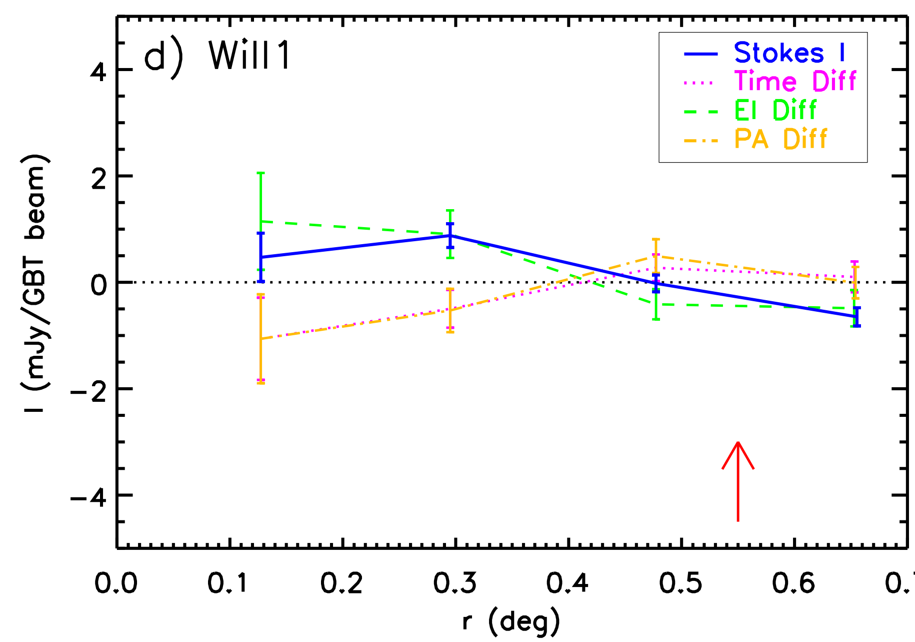






Synchrotron radiation from dwarf galaxies

Colafrancesco, Profumo, Ullio '07

$$D(E)\nabla^2\psi(r,E) + \frac{\partial}{\partial E}\left[b(E)\psi(r,E)\right] + Q(r,E) = 0 \qquad \psi(r,E) = dn/dE$$

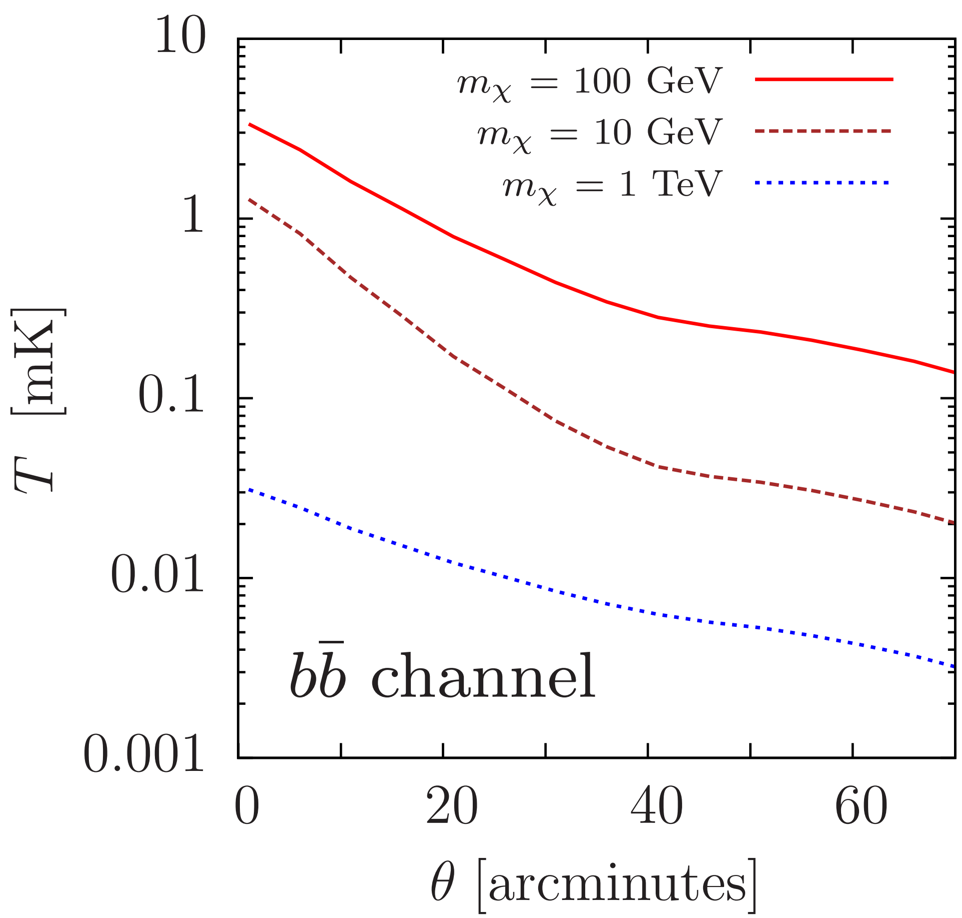
Diffusion　　Energy loss　　Source

Diffusion co-efficient:
Milky Way D ≈ 0.01 kpc^2/Myr. Donato et al. 2004

Magnetic field: B = 2.8 ± 0.7 μG for IC 1613
B = 4.0 ± 1.0 μG for NGC 6822
B = 3.2 ± 1.0 μG SMC

Chyzy et al. 2011

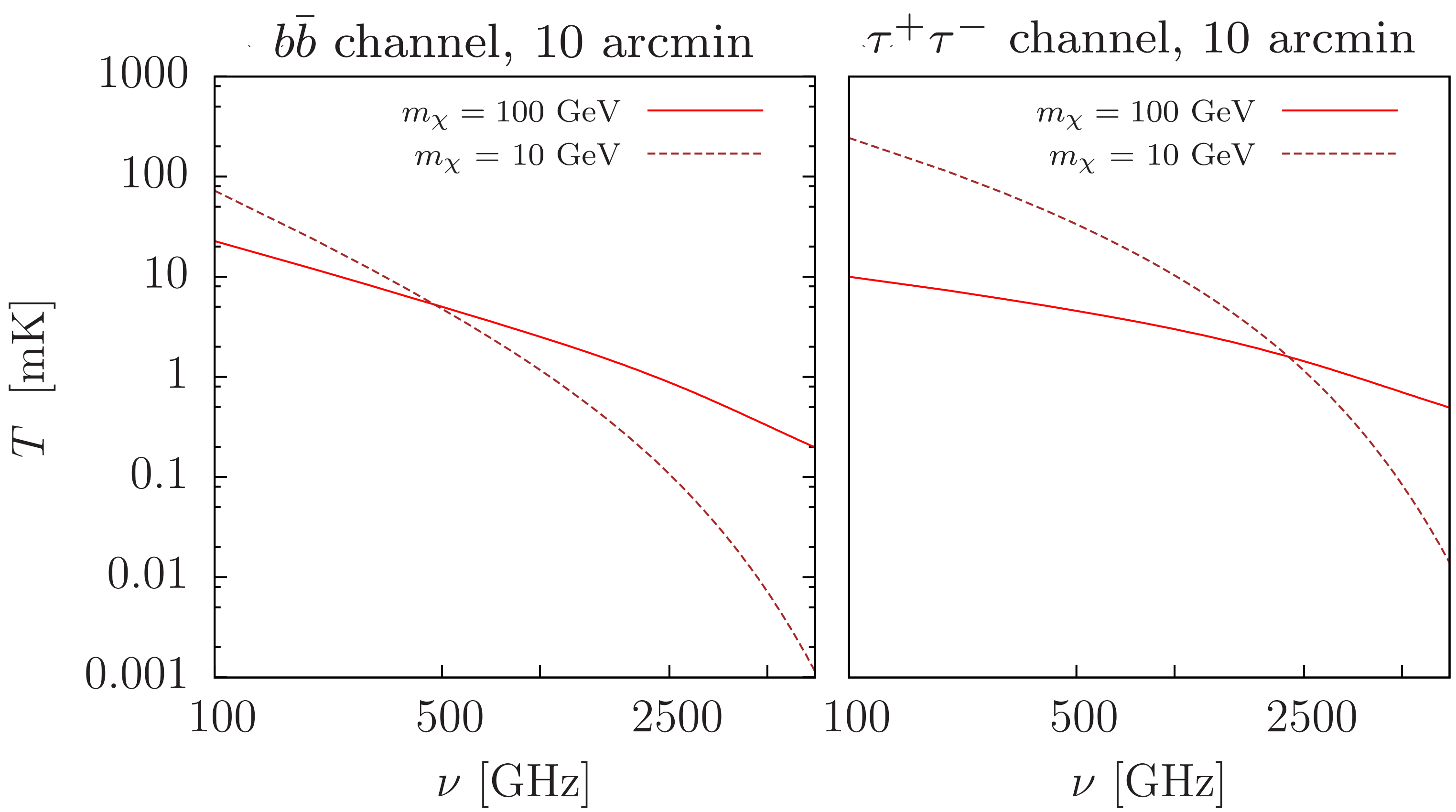
Synchrotron radiation from dwarf galaxies



Draco dSph at 1.4 GHz

$$n_\chi = \rho / m_\chi$$

But small WIMP mass
=> Soft spectrum.



Modeling dwarf galaxies

NFW: $$\frac{\rho}{\rho_{\mathrm{s}}} = \frac{1}{\left(\frac{r}{r_{\mathrm{s}}}\right)\left(1+\frac{r}{r_{\mathrm{s}}}\right)^2}$$

1. Mass within 300 pc (Strigari et al, Walker et al.)
2. The J factor (Fermi, Ackermann et al.)

$$J = \int d\Omega \int_{\mathrm{los}} ds\, \rho_{\mathrm{dm}}^2(s)$$

What about a core ?

Modeling dwarf galaxies

$$\frac{\rho}{\rho_s} = \frac{1}{\left(\frac{r+r_{\rm core}}{r_s}\right)\left(1+\frac{r+r_{\rm core}}{r_s}\right)^2}$$

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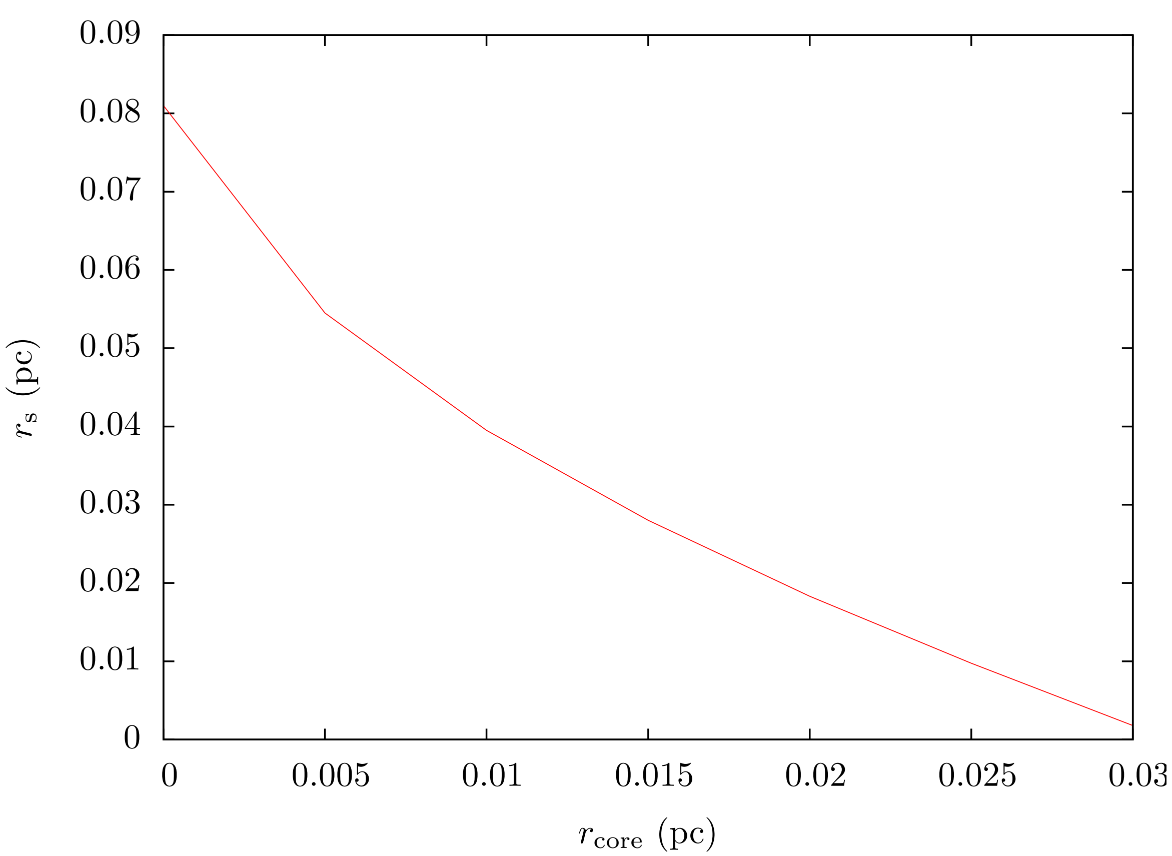
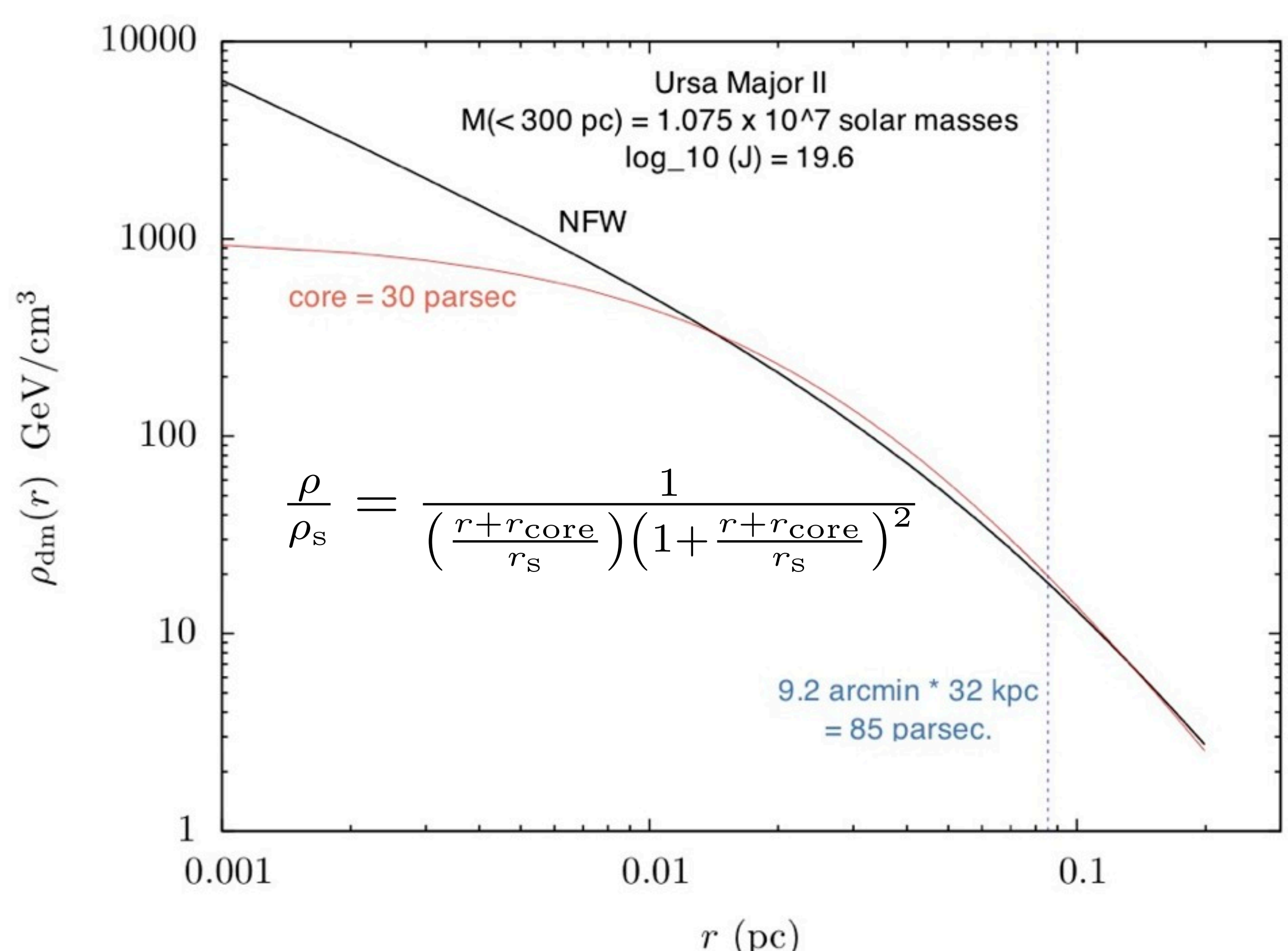
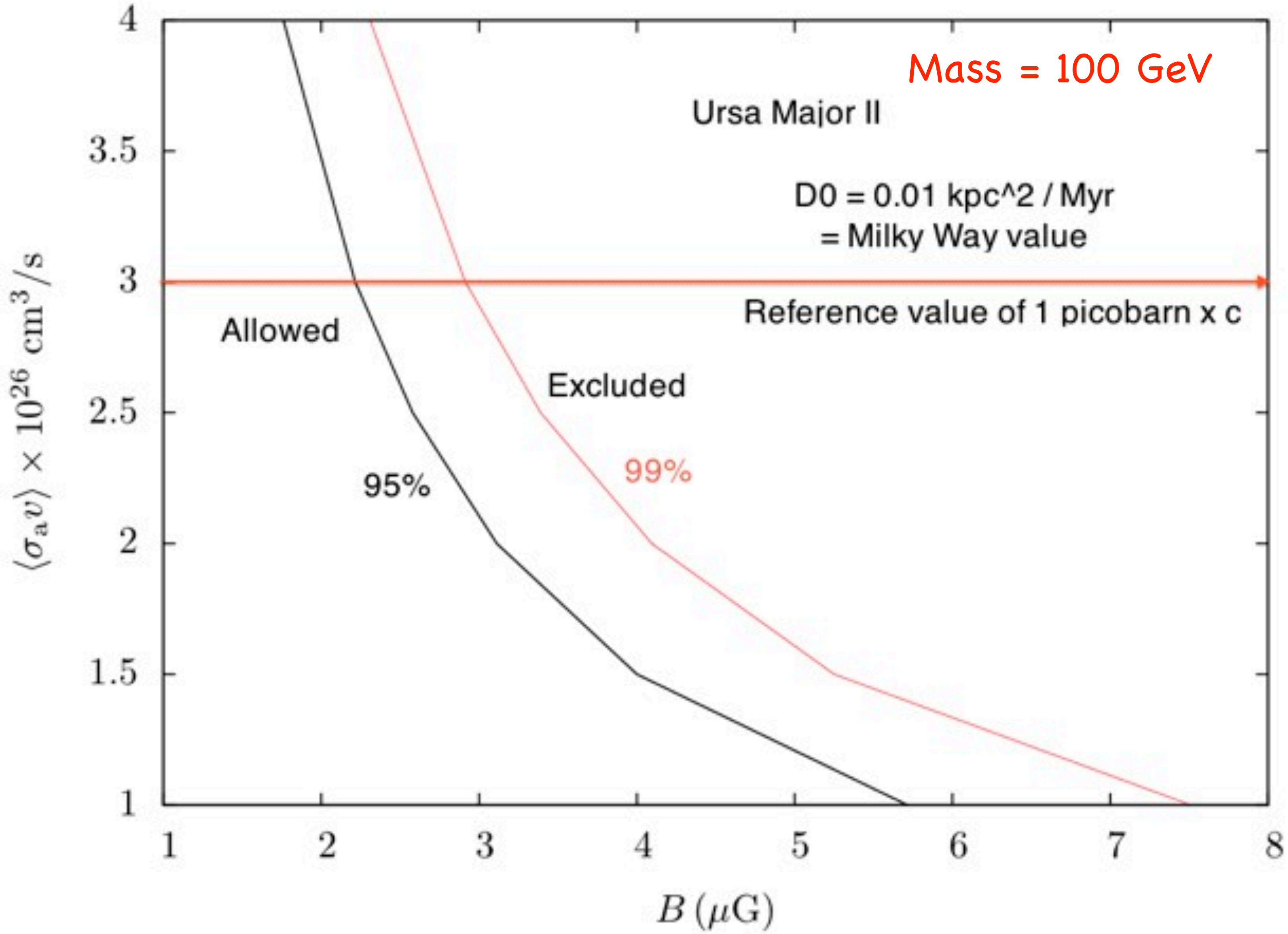




Constraints on DM annihilation from GBT observations of Ursa Major II: 20 hours

A.N., Peterson, Voytek, Spekkens, Aguirre, Mason, in preparation.

preliminary !!!



$\langle\sigma_a v\rangle < 3 \times 10^{-26}$ cm^3/s

for $m_\chi = 100$ GeV for B = 2.1 uG

The particle nature of Dark Matter:

What are the collider signatures of a WIMP of cosmological significance ?

Collider searches

Let's consider a well motivated theory:
the MSSM

2 Higgs doublets:	2 neutral CP-even	h, H	$\tan\beta = v_u / v_d$
5 Higgs bosons !	1 neutral CP-odd	A	
	2 charged.	$H^{\pm}$	

$$\chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}_3 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$$

Non-Decoupling regime: HEAVY CP-even Higgs is SM like.
$M_A \sim M_H < 130$ GeV. Low mass DM.

Decoupling regime: LIGHT CP-even Higgs is SM like.
$M_A \sim M_H > 250$ GeV Heavy DM.

Theoretical parameter space:

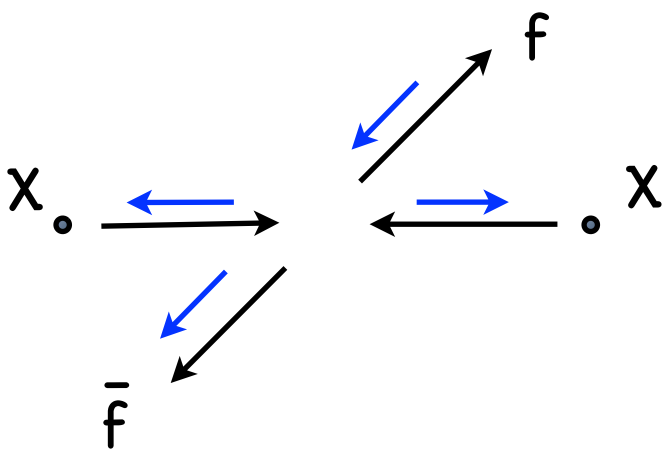
A.N., Tao Han, Zhen Liu, arXiv:1303.3040

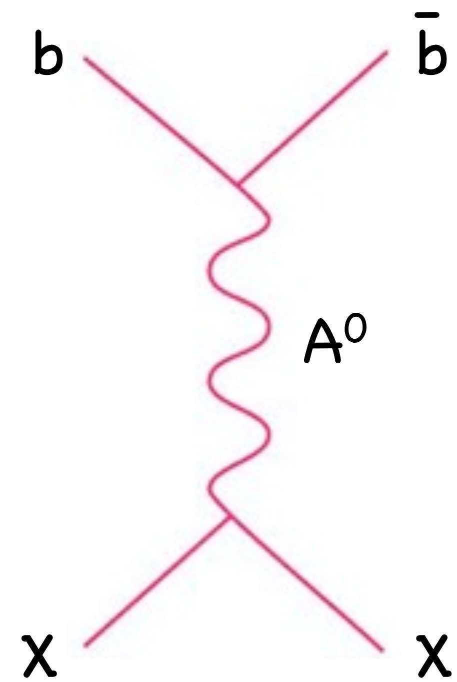
$$
\begin{array}{ll}
5\,\mathrm{GeV} < |M_1| < 2000\,\mathrm{GeV}, & 100\,\mathrm{GeV} < |M_2,\ \mu| < 2000\,\mathrm{GeV}, \\
3 < \tan\beta < 55, & 80\,\mathrm{GeV} < M_{\mathrm{A}} < 1000\,\mathrm{GeV}, \\
-4000\,\mathrm{GeV} < A_{\mathrm{t}} < 4000\,\mathrm{GeV}, & 100\,\mathrm{GeV} < M_{\mathrm{Q3}},\ M_{\mathrm{U3}} < 3000\,\mathrm{GeV}, \\
-4000\,\mathrm{GeV} < A_{\mathrm{b}} < 4000\,\mathrm{GeV}, & 100\,\mathrm{GeV} < M_{\mathrm{D3}} < 3000\,\mathrm{GeV}, \\
-4000\,\mathrm{GeV} < A_{\tau} < 4000\,\mathrm{GeV}, & 100\,\mathrm{GeV} < M_{\mathrm{L3}},\ M_{\mathrm{E3}} < 3000\,\mathrm{GeV}.
\end{array}
$$

phenomenological MSSM.
Lower bounds from collider searches
Upper bounds from naturalness arguments.

Low mass DM annihilation:

LSP is a Majorana fermion:
Annihilation to light fermions is helicity suppressed.





Amp $\sim \tan\beta$

Correct relic density
for low mass WIMPs:
High $\tan\beta$
Low M_A

$B_s \to \mu^+\mu^-$ Very sensitive to $\tan\beta$ for small M_A

$$A^0 \to b\bar{b}; \quad \tau^+\tau^-$$

Non observation of CP-odd Higgs decay at LHC.

We look for solutions that satisfy

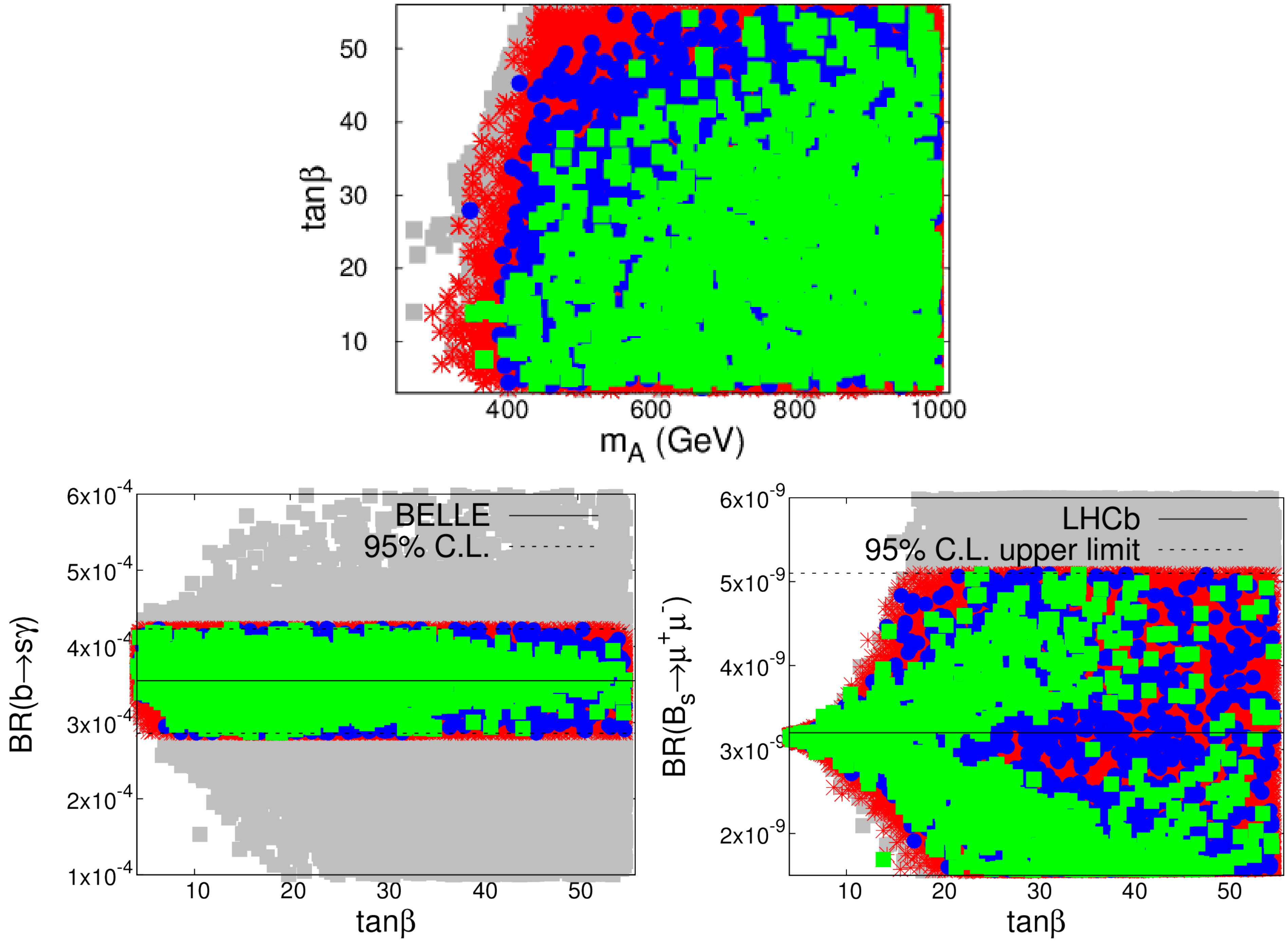
- DM relic density consistent with WMAP + LSS.

- 123 GeV < M_h < 128 GeV and $\sigma_{\gamma\gamma} > 0.8 \times$ SM
  plus Higgs search bounds from LEP+Tevatron+LHC
  plus LEP bound on the chargino mass > 100 GeV
  and the slepton mass > 80 GeV

- LHCb: BR ($B_s \to \mu^+\mu^-$) < 5.1 x 10-9
  Belle / Babar $2.31 \times 10^{-4} < BR(b \to s\gamma) < 4.51 \times 10^{-4}$

- SI scattering c/s consistent with XENON - 100.

- SD scattering c/s consistent with IceCube.
  Ann. c/s consistent with Fermi.

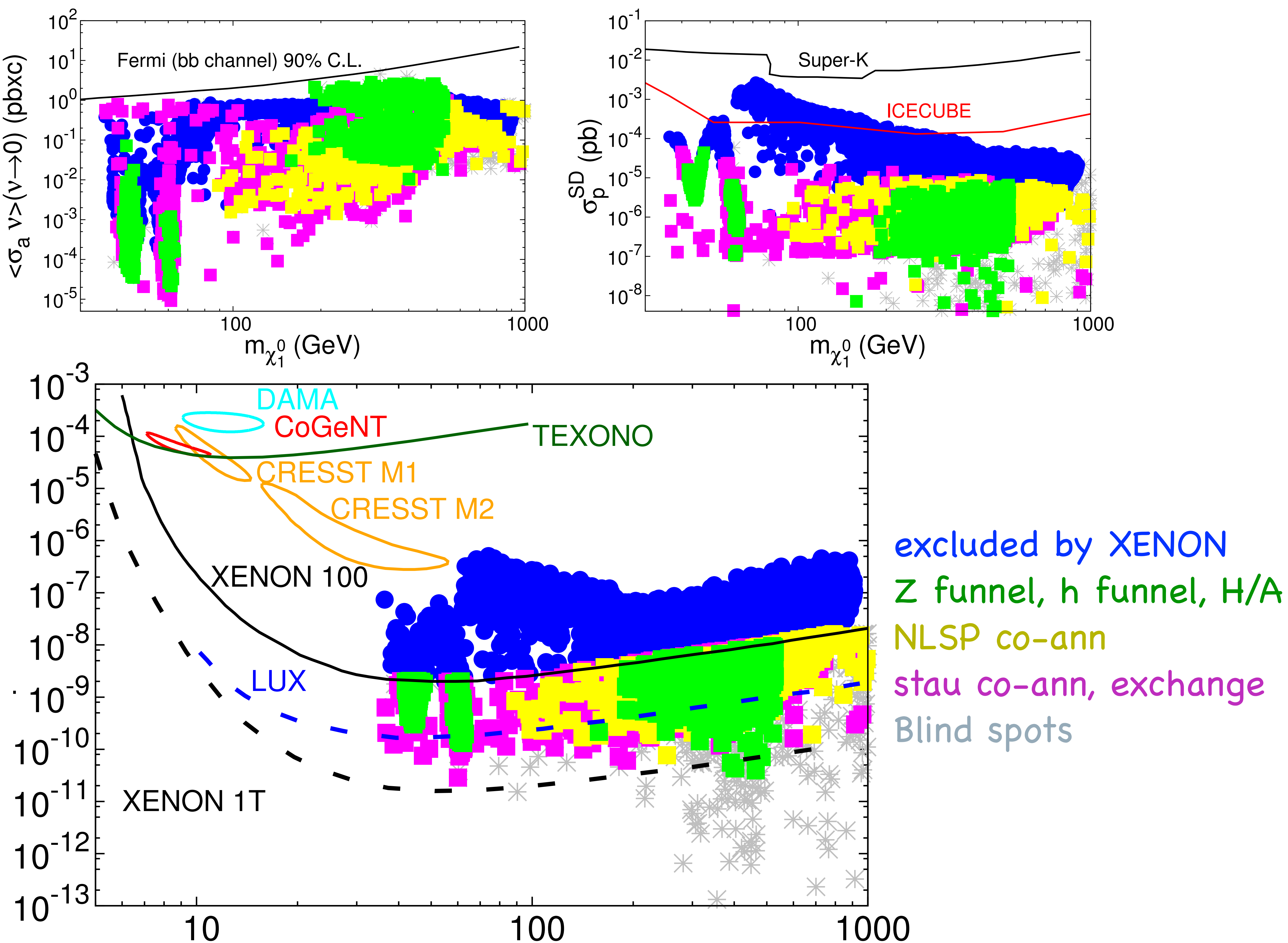


Gray points: Consistent with collider Higgs + doesn't overclose.

Red: Also consistent with b-flavor constraints.

Blue: + correct relic density.

Green: + XENON-100 bounds.



Fermi (bb channel) 90% C.L.
<σ_a v>(v→0) (pbxc)
m_χ1^0 (GeV)
Super-K
ICECUBE
σ_p^SD (pb)
m_χ1^0 (GeV)
DAMA
CoGeNT
TEXONO
CRESST M1
CRESST M2
XENON 100
LUX
XENON 1T
excluded by XENON
Z funnel, h funnel, H/A
NLSP co-ann
stau co-ann, exchange
Blind spots

Conclusions

- WIMPs are well motivated dark matter candidates.
  We may search for WIMPs using many techniques.

- The CMB is a very clean probe of low mass WIMP dark matter.
  Current limits from WMAP-9 + SPT + BICEP + QUAD
  disfavor WIMP mass < 10 GeV.

- Larger WIMP masses must be probed by other means
  --> A very way is by measuring the synchrotron emission
  from DM dominated, low background objects like the dSphs.
  100 GeV WIMP disfavored if magnetic field ~ 2-3 uG !

- Collider searches can give us complementary information.
  LHC + LEP + BELLE / Babar exclude low mass WIMPs in the MSSM.